WIK-Consult • Report

Study for Vodafone

Architectures and competitive models in fibre networks

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Executive Summary

With the finalization of the EC's NGA Recommendation there is much debate about how to best deliver the next generation of high-speed broadband networks. Actual FTTH roll-out, however, remains limited in Europe, with most of it based upon GPON technology.

The high capital costs and the long asset life of fibre mean that the technology choices made today will dictate the forms of competition and regulation that develop in these markets for years to come.

This report examines the cost differences and competitive outcomes for different FTTH technologies to determine the impact different technology choices might be expected to have on prices, market entry, penetration and market shares over the long term. Understanding these issues should help policymakers decide whether they should be incentivising particular technology choices today in order to maximize consumer surplus and total welfare in the future.

The various technology scenarios we modelled are:

Technologies suitable for unbundling[1]:

Incumbent	Competitor (Entrant)
Ethernet P2P[2]	Fibre LLU at MpoP
GPON over P2P[3]	Fibre LLU at MPoP
WDM PON	WDM unbundling at Core Nodes

Bitstream-only technologies[4]:

Incumbent	Competitor (Entrant)
GPON	Bitstream access at Core Nodes
GPON	Bitstream access at the MPoP

1 While these technologies have been modelled on the basis of entrant unbundling, this does not preclude, of course, additional bitstream-based entry.

2 P2P – Point-to-Point; PMP – Point-to-Multipoint.

3 This consists of a physical Point-to-Point architecture but with the incumbent using GPON plant "moving the splitters back" to the MPoP with dedicated fibre links in both the drop and feeder segments. Further details are provided in Chapter 2.

4 Due to the underlying Point-to-Multipoint fibre plant GPON cannot be unbundled at central sites. Accordingly wholesale access is bitstream-only.

The modelling approach

Our basic cost modelling relied upon a bottom-up cost modelling consistent with a Greenfield Long Run Incremental Cost approach[5]. We considered both a static model where the relevant FTTH roll-out is completed and the network has (fully) substituted the copper access network and a dynamic approach which considered the time path of investment according to a particular roll-out over time. For purpose of this study we created a hypothetical country of approximately 22 million households referred to as "Euroland". We defined 8 areas or clusters, each having typical network parameters derived out of detailed geo-modelling of access networks in several actual European countries. To determine the extent of viable roll-out we then modelled the total cost of providing NGA services in each cluster and assessed its profitability against demand represented by a typical ARPU of €44.25 per customer per month while entrants earned a 5% lower ARPU.[6]

These cost modelling results provide an indication of the competitive conditions we might expect in the NGA market for each technology as the critical market shares for viability indicated the potential number of competitors which could be supported.

We then developed two competition models which show the strategic interaction between the infrastructure provider and its competitors allowing end-user prices, consumer and producer surplus for all technologies to be compared.[7] We considered models both with and without a second vertically integrated broadband infrastructure (representing cable) to which no other firms have access. The "with cable" model is known as "No-Hinterland", while that without cable is the "Hinterland" model. In both types of models the number of entrants is determined endogenously.

Overall results

Our overall results reveal a clear distinction between technologies that can be physically unbundled and those bitstream-only technologies that cannot.

1. Scenarios based on networks suitable for unbundling generate greater consumer surplus and total welfare than those based on GPON bitstream access.

While our results are less clear on which technology suitable for unbundling should be preferred, this is an important conclusion for European policymakers because it sug-

5 As there often is available infrastructure from existing networks which may be reused to generate investment savings we also undertook Brownfield sensitivity calculations.

6 In the dynamic extension of the model we accounted for growing demand over the 20 year period of the model up to a maximum of 70% penetration.

7 In our competitive models, the incumbent owns and invests in an FTTH network to which entrants must obtain access in order to provide NGA services. As we found that infrastructure replication is only theoretically viable in the densest cluster we do not consider it to be of major relevance to FTTH competition so did not consider it further.

gests that the current trend – towards bitstream-only GPON – is clearly inferior to any option that is suitable for unbundling. Such architectures, whether P2P, GPON over P2P or WDM PON would deliver greater consumer surplus and total welfare. P2P architectures are available today, but WDM PON would require the adoption of new standards in Europe.

In addition, we find in our modelling that

2. GPON (i.e. closed and not suitable for unbundling) is only about 10% cheaper to roll-out than Ethernet P2P so open technologies can achieve the same coverage as closed GPON. In our basic model, the benefits of Ethernet P2P outweigh the additional investment costs and deliver higher consumer surplus and total welfare.

3. Proper pricing for wholesale access is essential, with a particularly strong impact on the unbundling options. Increasing wholesale prices by 10% can have a significant impact on the critical market shares for entrants and their competitive coverage at the given ARPU.

4. Under other assumptions, WDM PON would be the best choice if that technology becomes commercially available for the access network.

Networks suitable for unbundling generate greater consumer surplus and total welfare.

The table below summarizes our basic model results for monthly consumer surplus (CS) and total welfare (W) per month.

	Hinterland ("no cable")					No-Hinterland ("with cable")				
		CS		W			CS		W	
Scenario	Entrants	Mio €	Rank	Mio €	Rank	Entrants	Mio €	Rank	Mio €	Rank
P2P unbundling	3	243.1	2	279.2	2	4	466.9	1	490.3	2
GPON over P2P unbundling	3	245.6	1	283.6	1	3	434.0	2	493.8	1
WDM PON unbundling	4	240.5	3	270.8	3	4	431.2	3	473.9	3
GPON Bitstream Core	4	216.8	4	247.7	4.5	4	400.5	5	445.7	4.5
GPON Bitstream MPoP	3	208.6	5	245.4	4.5	4	416.0	4	445.1	4.5

In terms of total welfare, P2P architectures provide the best results, with GPON over P2P unbundling narrowly beating Ethernet P2P unbundling, while WDM PON ranks consistently third both for total welfare and consumer surplus, usually with a significant margin.[8] The two bitstream scenarios compete for last place.

We ran a number of sensitivities in addition to the base-case results reported in the table above including the quality of service deliverable by the various architectures, customers' willingness to pay for greater quality and the incumbency advantage. Considering the consistency of rankings for consumer surplus and total welfare across these sensitivities we found:

(i) WDM PON unbundling always comes up among the best;

(ii) P2P unbundling shows a variable ranking, but is usually in the first tier;

(iii) GPON over P2P unbundling is also quite variable but mostly ahead of P2P;

(iv) GPON with bitstream access at the core is as variable as P2P, but it shows up mostly in the second tier and would rank even worse under weak regulation; and

(v) GPON with bitstream access at the MPoP is always among the lowest-ranked.

In every scenario we modelled, the technologies suitable for unbundling ranked well above the bitstream-only options.

The additional cost involved in rolling out P2P is only about 10% higher than the one associated with closed GPON: technologies suitable for unbundling can achieve nearly the same coverage as closed GPON architectures.

Incumbent coverage of FTTH could reach up to 64% of the population with no noticeable difference between architectures suitable for unbundling and GPON.

We assume that the fixed network can reach a market share of up to 70% of the total potentially addressable market with the remainder representing DOCSIS 3.0, mobile broadband and non-subscribers. On this basis and assuming our ARPU projections, an incumbent operator can profitably cover a significant part of Euroland with FTTH - about 50% of the population could be covered with P2P or WDM PON while about 64% could be covered with GPON over P2P (or closed GPON). If WDM PON customer premises equipment (CPE) costs could be reduced to the level of GPON CPE, this technology could also cover around 64%. If ducts are available for re-use, coverage can generally

8 The margin is narrow for CS in the Hinterland model, because here WDM PON has 4 entrants, while the two P2P scenarios only have 3 entrants.

be extended one additional cluster (Less Suburban) with the greatest impact on the WDM PON case.

The cost comparison of our five scenarios has shown that overall GPON is the cheapest technology, followed by GPON over P2P, WDM PON and P2P.[9] A P2P fibre architecture requires only slightly higher costs than a closed GPON architecture in the range of 10%, reducing to around 7% if one takes account of the relative timing of investment between architectures. GPON over P2P generates savings compared to an Ethernet P2P architecture further reducing its investment gap with closed GPON.

This result can be understood because the network elements which cause the highest investment requirements, in-house cabling and drop cable, account for ~75% of total investment and these do not differ between any of the architectures.

Cost items like energy and floor space exhibit significant differences among architectures. Ethernet P2P causes nearly double as much energy cost at the MPoP as GPON and nearly 6 times higher energy costs than WDM PON (in terms of present value). P2P has more than 2.5 times higher floor space costs than closed GPON and nearly 90 times more than WDM PON. These apparently huge differences, however, only have a very limited impact on the overall cost performance of different architectures because the cost share of each of these factors is not more than 1%.

Proper pricing for access is essential.

In our basic models we assume that wholesale access charges are determined according to a Greenfield BU-LRIC cost standard. However, as the policy approach to wholesale charges as well as national specificities, topology, the speed of deployment and copper switch-off will all, of course, influence these wholesale prices which should not be simplistically interpreted as the ‘right’ price for fibre access.

Because of information asymmetries between the incumbent and the regulator, identifying the proper level of the LRIC in a newly emerging network may be a difficult task. Furthermore, there is currently a policy debate on explicitly deviating from LRIC to incentivize FTTH investment. Entrants may have to pay a mark-up on the LRIC based wholesale access charge. We have tested the impact of such policies on competition and welfare on the basis of our modelling approaches.

We find that, based on a given ARPU, increasing the wholesale prices moderately by 10% has a significant impact on the critical market shares and the competitive coverage with the strongest effects occurring in the P2P unbundling scenarios at the given ARPU. The competitive business model would become unviable except in the two most urban areas (18% population coverage). In the bitstream access scenarios the viability of

9 With the exception of the densest urban cluster where WDM PON and GPON over P2P switch ranks, this is consistent over the relevant clusters.

competition is removed from the Suburban area- some 11% of the total population. The general increase in critical market shares indicates a lower number of potential competitors and an increase in risk of insufficient market entry.

Under other assumptions WDM PON could be the best choice, if that technology becomes commercially available for the access network.

The ability to consolidate MDF locations should make WDM PON even more attractive to incumbents.

As WDM PON is expected to enable far longer line lengths and much higher splitting ratios, an incumbent rolling out WDM PON will be able to close many MDF locations and greatly aggregate demand in the remaining nodes. The incumbent might then be expected to realise profits when selling former MDF locations. Such profits have been integrated into our analysis by diminishing the discounted total expenses of rolling out WDM PON. With these profits incorporated into the analysis, WDM PON becomes the most attractive architecture in Cluster 1, becomes second in Cluster 2 and generally reduces the difference to GPON significantly. This may, however, strand the assets of entrants who have invested in active equipment at the MDF.

The relative performance of WDM PON is strongly influenced by the cost of customer premises equipment (CPE).

WDM PON viable market shares are actually lower than bitstream across the first 4 clusters but then jump significantly in Cluster 5 (Suburban). Should WDM PON vendors be able to reduce CPE prices to the level of GPON CPE the critical market shares for viability would be significantly reduced and coverage could be extended by one cluster to Cluster 6 - equivalent to the coverage achievable by GPON and at a slightly lower viable market share. Entrants could penetrate to Cluster 5 (Suburban) with viability at only 12% market share compared with 16% or 28% for GPON bitstream access at the core or MPoP respectively. Generally, WDM PON would then rank first as a technology. Getting WDM PON CPE costs down will require activity in the standards arena.

Notwithstanding these potential developments of WDM PON, the relative attractiveness of it against P2P is strongly influenced by assumptions made on consumers' willingness to pay for additional quality, the advantages conferred to the incumbent by its brand (known as the incumbency premium) and the technical performance which may be achieved by WDM PON. If, by the time the network is fully rolled-out (after about 10 years) consumers ascribe a high value to ultra high speeds and strongly differentiated retail offerings, then the additional cost of P2P is a price worth paying. If, on the other hand, consumers ascribe only a small value to these attributes, or entrants cannot reach the market shares required for viability, then the savings achievable under WDM PON, while still allowing a form of unbundling, make WDM PON the best technology to maximize consumer surplus and total welfare.

1 Extended Summary

FTTH architectures

1. In this study we consider and evaluate NGA architectures which meet the foreseeable future bandwidth demand and allow for highest bandwidth and quality for end-users and which no longer rely on copper cable elements. These are FTTH architectures only. From all available FTTH architectures we concentrate on the two most relevant architectures in Europe, Ethernet Point-to-Point and GPON. In order to overcome some restrictions and weaknesses being discussed for GPON we also include into our considerations two (G)PON variants, one implementing GPON on top of a passive Point-to-Point fibre plant and a future version of PON, increasing the bandwidth and quality of the current PON systems by using WDM technology on a Point-to-Multipoint fibre topology.

2. We assume the incumbent to be the investor in the NGA network infrastructure. Competitors (new entrants) face the same (efficient) cost if they offer FTTH services on the basis of wholesale access to the incumbent's network, but may achieve a lower ARPU. If the NGA architecture is based on a Point-to-Point fibre plant we have modelled the competitors as using unbundled fibre loops as the wholesale access service. If the architecture is based on a Point-to-Multipoint fibre plant, we consider an active wholesale access at the MPoP or at the core network node locations. In total we consider the architectures and wholesale scenarios as presented in Table 1-1.

Table 1-1 Overview of the architecture scenarios considered

Scenario name	Incumbent architecture	Competitor (Entrant) wholesale base
P2P unbundling	Ethernet P2P	Fibre LLU at MPoP
GPON over P2P unbundling	GPON over P2P	Fibre LLU at MPoP
WDM PON unbundling	WDM PON	WDM unbundling at Core Nodes
GPON bitstream core	GPON	Bitstream access at Core Nodes
GPON bitstream MPoP	GPON	Bitstream access at the MPoP

3. A P2P FTTH fibre architecture deploys individual fibre access lines from the MPoP to each customer home. The complete fibre capacity is available for each customer in the subscriber access network since every customer has a dedicated fibre from his home to the MPoP. Because of the uncertainties of the future bandwidth needs of residential and business customers this Point-to-Point fibre plant appears to be the most future proof solution, since the use of the full optical spectrum per fibre is not restricted by any intermediate technology. MPoPs can serve more fibre links than the largest copper MDFs, which causes therefore no problem of manageabil-

ity. In this architecture the capacity of the fibre can easily and flexibly be expanded by dedicated port equipment. The architecture supports a high security standard.

4. A P2P architecture provides easy unbundled access to the individual fibre line at the MPoP. The competitor just has to install his own Optical Distribution Frame collocated at the incumbent's MPoP, where he then operates his own Ethernet Switch.

5. The GPON technology is designed for Point-to-Multipoint fibre plants. It concentrates the traffic of a significant number of customer access fibres at an intermediate optical splitter location (DP) onto a single backhaul fibre. Optical splitters may be cascaded in order to optimize the fibre count and to adapt it to the end customer distribution. Thus, the fibre plant strongly depends on the optical power budget and the maximum splitting factor. The fibres from the splitters are connected to the customer side of the ODF in the MPoP and patched there to the appropriate OLTs. The OLTs are connected to an Ethernet switch which is the interface to the concentration network. Especially during ramp-up when only few potential customers have become subscribers to the FTTH network this architecture still has considerable spare capacity. GPON systems offer a downstream bandwidth of 2.5 Gbps as shared capacity. In the case of 64 end customers per splitter thus the system supports an average capacity of 40 Mbps for each user. GPON architectures concentrate the traffic onto fewer electronic interfaces at the Central Office than Ethernet P2P. These active components are more complex and more expensive than P2P components, but fewer components are needed. Also the end-user devices are more expensive.

6. GPON systems are more vulnerable to illegal interception, denial of service attacks and more difficult to repair because all users connected to one splitter share the same bandwidth. GPON architectures are well suited to asymmetric traffic, inasmuch upstream and downstream bandwidths differ due to the inherent upstream communication collision. A preponderance of downstream traffic over upstream has so far been the typical residential behavior. Insofar as customer demand moves more towards symmetric traffic patterns, the GPON architecture loses relative performance. The ability of GPON to serve end customers with individual services and bandwidth guarantees is restricted. An increase in bandwidth can be achieved by reducing the splitting factor (the number of customers per OLT) and/or by allocating fixed bandwidth through the OLT administration, or even supplying TDM based services. But the more bandwidth that is allocated to a particular customer, the less that is available to be shared by the others.

7. GPON, deployed with splitters in the field, can at present only be unbundled at the splitter locations close to the end customers. Fibre sub-loop unbundling is not considered in this study as it does not appear to support a sufficiently profitable competitor's business model.

8. Instead of unbundling we consider two bitstream access scenarios in the GPON case, bitstream access at the core network level and at the MPoP level for the competitors' wholesale access cases. The main difference between these scenarios is that the bitstream access at the core level includes the transport through the incumbent's concentration network while in the scenario bitstream access at the MPoP the competitor has to use his own concentration network and may obtain a transparent, non-overbooked bandwidth from the MPoP to his end customers, resulting in higher product quality and the ability of independent product design compared to GPON bitstream access at core nodes. But since the competitor still depends on the incumbent's active components, this quality improvement will not achieve the degree of unbundled fibre local loops.

9. GPON can also be implemented on top of a Point-to-Point fibre architecture by "moving the splitters back" into the central MPoP location and having dedicated fibres in both drop and feeder sections. We consider this combined P2P/GPON architecture because it has the potential to combine advantages of both worlds. All fibres are terminated on the customer sided ports of an ODF and are accessible per patch cables. So every customer still has a dedicated fibre line to the MPoP, thus opening all future fibre and optical spectrum uses one may imagine and also allowing individual use of a single fibre as described in the P2P scenario. Beside this additional option individual customer demand may be served out of the GPON features as described before, whereby the reduction of the splitting ratio could be achieved in an easy manner at the central site just introducing new splitters without affecting the fibre plant in the field. Locating the splitters at a central site allows a more efficient use of the splitters and the OLTs during the roll-out of the services (ramp-up). This generates not only positive cash flow effects but also reduces some risk of investment. The flexibility of the Point-to-Point fibre plant allows one to exchange the transmission systems smoothly over time, customer per customer, if that looks favourable, and thus reduces the supplier dependency of the operator.

10. The associated wholesale product we have considered in this study is an unbundled fibre loop. From a wholesale perspective GPON over P2P is identical with the Ethernet P2P case because it refers to the same P2P outside plant.

11. The fourth architecture we consider and assess is WDM PON. This technology would allow dedicated wavelengths for each customer, resulting in higher bandwidth compared to GPON. Each of these WDM PON wavelengths is announced to support 1 Gbps bandwidth, which can be administered by one or more WDM PON OLTs, operated by different carriers, thus allowing one to unbundle the wavelength. A single OLT will here support up to 1,000 wavelengths with 1 Gbps capacity each in a symmetric manner. The fibre plant may bridge a distance of up to 100 km allowing one to close down all the existing MDF locations except those few for the core network. With this type of WDM PON architecture we have a dramatic increase of dedicated bandwidth per end customer (from 40 Mbps to 1 Gbps) but the

bandwidth peak per customer is reduced to 1 Gbps compared to 2.5 Gbps in the shared GPON case.

12. WDM PON enables a specific unbundling option at the core locations. The associated wholesale access considered is an active line access at the core level, which we call “WDM PON unbundling”.

13. Table 1-2 provides our assessment of the relative performance of the four fibre NGA architectures considered in this study on the basis of 10 key performance indicators. This assessment still is qualitatively. Insofar as the indicators relate to investment and cost they will be quantified in a cost modelling approach developed for this purpose. Thereby also the relative importance of the indicators can be and will be taken into account.

Table 1-2: Comparison of access architectures considered

	P2P	GPON over P2P	GPON	WDM PON
Fibre count drop / feeder	◑ / ○	◑ / ○	◑ / ●	◑ / ●
Bandwidth per customer / capability for symmetry	● / ●	◑ / ◑	◔ / ◑	◕ / ●
Max distance from MPoP to customer	10-40km	20km	20km	100km
Ability to cater to business customers	●	◕	◔	◑
Future-proof	●	●	◑	◑
Security	●	◑	◑	◕
Degree of vendor-independency	●	◔	◔	◔
Energy consumption MPoP	○	◕	◑	●
Fault identification and repair	●	◑	◔	◔
Floorspace demand at MPoP	○	◑	◕	●

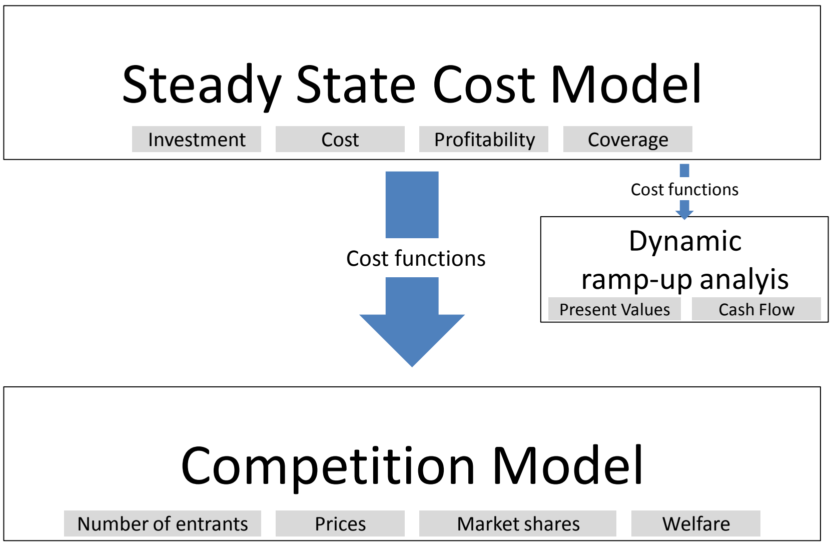
Relatively good ● **Relatively poor** ○

14. We have not considered and assessed FTTN/VDSL, Active Ethernet, Multi-fibre deployment, FTTB and EPON technologies in this study. These technologies either do not match the long-term capacity requirements of FTTH (FTTN, Active Ethernet, FTTB), are less flexible in customer individual solutions and not or only rarely used in Europe (EPON) or we have dealt with them already extensively elsewhere (Multi-fibre deployment).

Modelling approach

15. We have developed three partly interlinked modelling approaches to analyze the impact of different architectures and wholesale scenarios on investment, cost, profitability, reach, competition, market shares, pricing and welfare. We have used a steady state cost model that feeds cost functions into a strategic competition model. In addition, we have analyzed the impact of a ramp-up over time as an extension of the steady state model, the dynamic model. This model is not connected with the competition model. Figure 1-1 shows the relations between the three models and their primary outputs (grey).

Figure 1-1: Overview of modelling framework



16. Our basic modelling relies upon an engineering bottom-up cost modelling approach. We have modelled the total cost of the services considered under efficient conditions, taking into account the cost of all network elements needed to produce these services in the specific architecture deployed. This approach is coherent with a Long Run Incremental Cost approach as applied in regulatory economics.

17. Our model consists of a static and a dynamic approach. In the static model we compare the cost of a specific NGA deployment in a steady state. In the steady state the roll-out is completed and the FTTH network has (fully) substituted the copper access network. By increasing the market share in percent and comparing the resulting cost per customer with the fixed average revenues per customer we determine the point, where, if at all, the revenues equal the cost. This is the “critical market share” necessary to make the NGA business profitable and hence it deter-

mines the viability range of a network operator. Therefore we model the complete value chain of the operators. Contrary to the steady state model the dynamic approach considers the time path of investment according to a particular roll-out as well as the re-investment pattern.

18. According to the chosen LRIC approach we calculate the cost of each of the four architectures considered following a Greenfield approach. This means that the investor will construct a new, efficient state of the art network from the scratch, assuming that current existing infrastructure, if included in the new network, has to be considered at full current cost. However, in reality there often is available infrastructure from legacy networks which may be reused to generate investment savings. This possibility could have an impact on the investment decision. We analyze this aspect in a sensitivity calculation.

19. For purpose of this study we decided not to choose a dedicated European country but chose a settlement structure which is typical for European countries and designed the hypothetical country for approximately 22 million households or a population of around 40 Mio. inhabitants. This country is referred to as “Euroland”. We have defined 8 clusters, each having typical structural access network parameters derived out of detailed geo-modelling of access networks in several European countries on a nationwide basis. The geo-type characteristics rely on exact data from several countries. In that sense, “Euroland” is a generically representative European country. The clusters are composed in a way that they address similar numbers of potential subscribers.

20. To assess the relative performance of fibre technologies we modelled the total cost of providing NGA services. The access network is modelled in detail in a bottom-up approach. The cost model follows a Greenfield approach for all network elements. As a sensitity we also developed results of a Brownfield approach where the incumbent is able to save investment by using existing infrastructure without opportunity costs. Concentration and core network costs are approximated by a cost function consisting of fixed and variable costs. Besides scaling these cost functions they are the same for the incumbent and the entrant. Demand is represented by an ARPU per customer and month representing a relevant service customer type mix and amounts to 44.25 €. Due to brand and other competitive disadvantages entrants are assumed to achieve a 5% lower ARPU. Wholesale prices of the various access models are based on the LRIC of the network elements of the incumbent. They are calculated at a take-up rate of 70% of the FTTH network, a rate which is a bit less than the market share of the fixed network for all access lines today.

21. The different NGA architectures have a different time pattern of the investment regarding certain network elements. The steady state analysis is not able to cover this aspect. It may, however, have some impact on the relative (financial) performance of the architectures. We have therefore also developed a dynamic approach

which takes into consideration a ramp-up period to deploy the FTTH network. Besides a network deployment period this approach also takes into consideration that demand will be growing over time to reach the target level of a 70% take-up. The model takes a 20 year perspective and therefore also takes replacement investment of the electronic equipment into consideration.

Profitable coverage – Greenfield approach

22. We assume that the fixed network can reach a market share of up to 70% of the total potentially addressable market (access lines), an incumbent operator can profitably cover a significant part of Euroland with FTTH. The area of profitable coverage is relatively invariant of the FTTH architecture which is deployed:

    - P2P and WDM PON can be profitably rolled out up to our suburban Cluster 5 or for 50.7% of the population.

    - GPON over P2P and GPON can (theoretically) even be deployed up to our Less Suburban Cluster 6 corresponding to 64.4% of the population.

23. Even theoretically, a FTTH infrastructure can be replicated by a second investor only in the Dense Urban Cluster 1 or for 8.1% of the population. In all other viable areas the FTTH investor needs a critical market share of close to or above 50% to become profitable.

Profitable coverage – Brownfield approach

24. An incumbent usually can use existing network infrastructure to deploy a new fibre network. Potential savings due to existing infrastructure relate to trenches, ducts and manholes in all network segments. Potential investment or cost savings depend on the degree of ducting, the availability of (sufficient) spare capacity, the age structure of the passive network infrastructure and the degree of aerial deployment, where no savings through the use of already existing ducts can be achieved.

25. We assume that, where existing ducts are available, these ducts on average already have an average age of half of the equipment life time. Thus the use of existing ducts reduces the investment by (up to) 50%. Potential investment savings depend on the network segment and the architecture. We assume the following saving factors:

    - up to 50% in the backhaul (up to 100% ducts usable),
    - up to 50% in the feeder (up to 100% ducts usable),
    - up to 25% in the drop segment (up to 50% ducts usable).

Potential savings differ by architecture only in the feeder segment, for which we assume

- 10% for P2P and GPON over P2P (many fibres in the feeder segment)
- 50% for GPON and WDM PON (strongly reduced fibre count in the feeder segment)
- In the drop segment potential savings increase with customer density (due to less aerial and more ducts in the dense clusters).

26. Lower investment requirements in a Brownfield approach enable incumbents to increase the profitable coverage with P2P and WDM PON up to the Less Suburban Cluster 6.
27. For all technologies total costs and critical market shares decrease. The strongest effects occur for the WDM PON architecture. Total network costs here decrease by 5% (Cluster 1) to 11% (Cluster 8). The lowest cost savings occur with P2P from 4% (Cluster 1) to 7% (Cluster 3). Cost savings for GPON are higher than for P2P but lower than for WDM PON, and range from 5% (Cluster 1) to 9% (Cluster 4).
28. The investment savings become more transparent by segment:
    - The effective reduction in the drop segment ranges from 7% to 20% depending on the cluster, and is similar for all architectures, since the architectures do not differ in this segment and the differences between the clusters depend on the different degrees of aerial cabling per cluster.
    - In the feeder segment, the savings for P2P are around 7% and for GPON around 40%, because the probability of finding sufficient empty duct space for the higher fibre count of P2P is lower.
    - The savings in the backhaul segment amount to around 40% for WDM PON, since all fibres fit into existing ducts.
29. Even if one assumes a more aggressive approach by doubling the investment cost savings, this would not expand the area of profitable coverage beyond Cluster 6 for any of the architectures.

Potential for competition

30. Competition cannot follow the incumbent in all areas of the FTTH roll-out. Independent of the network architecture and the access scenario considered, the viability of any competitive model ends at least one cluster less than the viability of the incumbent's roll-out (also the theoretic maximum for the competitors).
31. The critical market shares of the different scenarios indicate that in all architectures and competition scenarios potentially several competitors could survive in the mar-

ket. The highest potential number of competitors may occur in the case of GPON bitstream access and WDM PON wavelength unbundling at the core.

32. As expected, business models on the basis of unbundling require (significantly) higher critical market shares than business models based on bitstream access. The unbundling model requires already a critical market share of 24% in Cluster 3, while bitstream access is viable at 4% to 8% critical market share in the same cluster.

33. Because the cost curve of competitors is relatively flat in the relevant range, only slight changes in the relevant parameters (e.g. ARPU) have a strong impact on the profitability. In case of unbundling, for instance, the critical market share jumps from 10% in Cluster 2 to 24% in Cluster 3. The structure of the cost curves in the relevant range makes unbundling a riskier business model than bitstream access.

34. If the wholesale prices also reflect the investment savings of the incumbent then costs and critical market shares of competitors decrease in all competition scenarios. In addition, they can also expand competitive coverage by one cluster with the exception of the LLU scenarios.

35. We have calculated the impact of deviations from LRIC based wholesale prices on the structural conditions of competition. Even a moderate increase of the wholesale prices by 10% reduces the viability of competition and the competitive coverage in most cases. The most significant impacts occur in the LLU unbundling scenarios. Critical market shares of competitors in all scenarios increase significantly.

36. Similar effects occur if the wholesale prices are calculated at a 60% take-up rate of the FTTH network instead of 70%. Wholesale prices will then increase by 10% to 13%.

Investment and cost differences

37. GPON requires the lowest investment compared to all other architectures which we consider. This result holds for each cluster (subscriber density). WDM PON shows the second lowest investments. The investment deltas between P2P and GPON, however, remain moderate and range from 2% (Cluster 8) to 14% (Cluster 1).

38. GPON over P2P generates relevant savings compared to a P2P architecture and requires only moderately more investment compared to GPON.

39. The overall investment deltas between the architectures are relatively small because the network elements which cause the highest investment requirements, in-house cabling and drop cable, account for ~75% of total investment and do not differ between architectures.

40. In order to better understand the relation between the architectures, it is worthwhile to look at the investment deltas in the different network elements. The main reason for the advantage of GPON compared to P2P and GPON over P2P results from the lower investment in port electronics at the MPoP. Feeder investment can become up to double as much for P2P than for GPON. However, feeder investment differences become relatively small in less dense clusters as the additional fibres for P2P do not necessitate additional civil works but cables only. This difference is overcompensated by the use of splitters in the outside plant for GPON. WPN PON suffers from the highest investment in CPE. P2P requires more than two times higher floor-space investment at the MPoP than GPON and nearly 40 times more than WDM PON. These huge differences, however, only have a rather limited impact on the overall investment performance of technologies, because the investment share of this element amounts to less than 1%.

41. The relative performance of WDM PON is very much affected by the cost of customer premises equipment. Should WDM PON vendors be able to reduce CPE prices to the level of GPON CPE the viability of WDM PON could be extended by one cluster to Cluster 6. In addition the critical market shares for viability could be reduced. Generally, WDM PON would rank first as a technology.

42. The cost structure of a competitor in a FTTH network is strongly dominated by the wholesale price. In the bitstream scenarios the cost share of the wholesale price amounts to ~65% (20% market share, Cluster 3). The cost share of the wholesale provision amounts to 57% in case of unbundling.

Dynamic considerations of investment and cost

43. Moving from a static to a dynamic approach, the time path of investment according to a particular roll-out and the re-investment pattern has some impact on the relative investment and cost performance of the different architectures.

44. The overall picture of the relative performance only changes moderately: GPON remains the technology with the lowest investment. WDM PON, however, loses some attraction and becomes the most investment intensive technology. This follows mainly from the higher cost of CPE equipment in case of WDM PON.

45. The time path of the investment differs to some extent between the architectures: Although most of the investment is front-loaded for all architectures, GPON has a lower amount of investment which is driven by the actual number of subscribers. While Ethernet ports in P2P are subscriber driven, GPON's investment in OLTs is not. The larger share of variable (subscriber driven) investment generates a slightly better risk profile for P2P compared to GPON.

46. Discounting future investment to a present value does not change the ranking between architectures, but the relative difference between P2P and GPON becomes smaller. It decreases from 10% to 7%. The same holds for WDM PON, which remains ranked as number three but the relative difference to GPON decreases to 5%.

47. Completing the picture by including all other network costs (including OPEX and common cost) besides investment, once again does not change the overall ranking of architectures: GPON remains the lowest cost technology, GPON over P2P comes next followed by WDM PON and P2P. The differences between technologies decrease if comparing total (discounted) expenses and investment. In relative terms, the difference in terms of present value of discounted expenses (Cluster 1 to 6) between GPON and GPON over P2P become negligible (~1%); P2P generates ~7% more expenses than GPON and WDM PON ~3% more.

48. Single cost items like energy and floor space exhibit significant differences among architectures.

    - P2P causes nearly double as much energy cost at the MPOP as GPON and nearly 6 times higher energy costs than WDM PON (in terms of present value)[10].
    - P2P has more than 2.5 times higher floor space costs than GPON and even nearly 90 times more than WDM PON.

    These huge differences, however, have only a very limited impact on the overall cost performance of architectures because the cost share of each of these factors is not more than 1%.

49. The incumbent might realize windfall profits when selling former MDF locations. Such windfall profits are not part of the decision relevant costs of a certain architecture. They have, however, to be taken into account in the decision making process of the investor. This is of particular relevance, if such windfall profits are different among architectures. Such windfall profits can conceptually consistently be integrated into our dynamic discounted cash flow analysis. They simply diminish the discounted total expenses of a particular architecture. In this model this is only relevant for the WDM PON case. On the basis of some plausible assumptions we assume a total net revenue of dismantling MDFs for the incumbent of 698 Mio. €, which are 279 Mio. € in present value given the assumed deployment path. These lump-sum profits have a relevant impact on the relative performance of WDM PON. WDM PON becomes the most attractive architecture in Cluster 1, becomes second in Cluster 2 and generally reduces the difference to GPON significantly.

10 CPE power consumption is not included, since we consider an operator's view.

The oligopoly modelling approach

50. The cost modelling results only generated a rough picture on the competitive conditions in the NGA market. It produced clear and definitive results on the replicability of FTTH fibre infrastructure. The critical market shares for viability indicated the potential number of competitors which could exist in the market on the basis of a certain business model. Furthermore, and most importantly, the cost modelling approach generated cost functions for the business models of the incumbent as the infrastructure investor and the access seeking competitors. These cost functions are developed for all architectural and all access scenarios we are considering in this study. The cost modelling approach, however, does not deal with the strategic interaction between the wholesale provider and the competitors. Only if that is taken into account, it becomes possible to predict the "real" market outcome in terms of prices, market shares, profits and the actual number of competitors in the market.

51. We have developed a strategic competition model which is capable to develop a steady-state model of competition in a FTTH oligopoly. The model is able to show the strategic interaction between the infrastructure provider and its competitors and allows comparing end user prices, consumer and producer surplus for all architectural and access scenarios. The focus will be on market outcomes for given investment decisions. The approach, however, will also allow us to quantify the gains from certain investment decisions. It can thus shed some light on investment incentives of the different market players. We can evaluate the effect of regulation on these gains from investment. The oligopoly model uses the output of the cost model, the cost functions of the various market players, as its basic and central input. Furthermore, the critical market shares are used to calibrate the initial number of operators in the oligopoly model.

52. Our modelling approach is based on the pyramid model, which is closely related to the spokes model: For each pair of services, there is a set of consumers who choose between these two products and these consumers are (uniformly) distributed in their willingness to pay for one service rather than the other. Graphically this leads to a pyramid with each service located at one of the tips of the pyramid. Our approach captures essential aspects of competition in FTTH markets, both on the wholesale and retail side. One firm, the "incumbent", owns and invests in an FTTH access network, to which other firms ("entrants") must obtain access in order to provide NGA-based services. Entrants are assumed to be symmetric and need to make own investments in order to use NGA access. We consider models both with and without a second vertically integrated broadband infrastructure ("cable"), to which no other firms have access. The services that firms offer are both "horizontally" and "vertically" differentiated. The former means that consumers do not react strongly to small price differences because individual preferences for firms' brands

differ. In particular, assuming a uniform distribution of individual tastes in this horizontal dimension leads to linear demand functions. As a result of horizontal differentiation, the market is imperfectly competitive and firms will enjoy positive markups. Vertical differentiation expresses differences in service quality and goodwill or brand recognition as perceived by consumers, i.e., at equal prices a firm with higher service quality would attract more consumers. Service quality is assumed to affect all consumers similarly, i.e. we abstract from market segmentation in the service quality dimension.

53. To model that total FTTH subscription demand is variable, we considered two model variants. In both there is a group of “competitive” subscribers. Each competitive subscriber makes a first choice between two of the firms, and unless their offers are very unfavorable, he will choose one of the two. It is assumed that all pairs of preferred firms (before quality differences) are equally likely in the population, so that effectively each firm will compete with any other firm for consumers. Formally speaking, cross price elasticities are different from zero for all product pairs. Due to the assumption of uniform distributions of consumer tastes, the resulting demand function of each firm is linear in its own price and linear in the price of all other firms. This makes the analysis tractable and allows for explicit solutions. In spite of advances in empirical demand estimation that allow for more flexible demand specifications, the linear demand system remains popular in empirical research. Our underlying micro foundation permits us to compare markets with different numbers of firms in a meaningful way. If the firms on the market include the cable firm, our model has the feature that FTTH subscription demand is variable. However, total demand for subscription is fixed and assumed to be 100% of potential subscribers in the clusters considered. We call this the “No-Hinterland” model. In the absence of a non-FTTH-based competitor, we make subscription demand variable with the introduction of “captive” consumers who make a choice between one firm and not buying FTTH subscriptions at all (this is the “Hinterland” model). In line with the critical market share analysis we aim at FTTH subscriptions close to 70% of all potential subscribers in the clusters considered.

54. The access tariff paid by the entrants to the incumbent consists of a price per subscription and potentially also of a fixed fee. In this study we have considered only linear wholesale access tariffs based on the incumbent’s LRIC at a defined network load. In one variant of the model, we determined the linear access tariff such that at the resulting equilibrium quantity, the access payments exactly cover the total cost of providing FTTH access (interpreted as LRIC pricing).

55. We treated the incumbent as if he were under vertical accounting separation into a NetCo that supplies FTTH infrastructure access and an OpCo that sells FTTH end-user services. The incumbent’s NetCo sells access to other firms (“entrants”) and to the OpCo. This does not affect pricing behavior and overall profits but it provides for an automatic price-squeeze test.

56. Depending on the scenario considered, first, firms make certain investments in networks and access, which determine their service quality levels and operating cost. Second, they compete in subscription fees at the retail level. The resulting market outcome is modelled as the Nash equilibrium outcome of the resulting pricing game, from which subscriber numbers, profits, market shares, consumer surplus and total welfare are derived. In the model with entry and exit, we first allow for a non-specified process of entry and exit with the feature that all active entrants make profits and that the entry of an additional entrant would lead to losses of all active entrants. Here we postulate that entrants foresee the effect of entry on the pricing decisions and, thus, on market outcome. Formally, and in line with the literature on industrial organization, this means that we consider subgame perfect Nash equilibria of the two-stage game in which entrants first make their participation decision and then all active firms make pricing decisions.

57. Besides the cost functions for the various market players and scenarios the quality of service and willingness to pay assumptions of the various scenarios form another basic input of the competition model. Our assumptions on quality of service (QoS) and the end-users' willingness-to-pay (WtP) are provided in Table 1-3. The values are in Euro-equivalent per month.

Table 1-3: QoS and WtP assumptions for basic model

QoS Scenario	Incumbent QoS =WtP	Cable QoS = WtP	Entrant QoS	Entrant WtP
P2P unbundling	100	82	99	97
GPON over P2P unbundling	99	82	99	97
WDM PON unbundling	95	82	91	89
GPON bitstream core	90	82	85	83
GPON bitstream MPoP	90	82	87.5	85.5

The value of chosen QoS differences may appear large from today's perspective. However, it has to be kept in mind that we are considering steady state situations with full FTTH penetration around ten years from now. It can be expected that the share of customers with high-bandwidth demands and the prevalence of corresponding applications will be much higher than now. Thus, the premium for ultra-high bandwidth will also be much higher than now. In contrast, the incumbency premium will likely become smaller, as time goes by. This justifies the small incumbency premium of 2 Euros over entrants that we have chosen.

Results on end-user prices

58. There are three drivers of prices and price differences: Costs, WtP and competition (number of firms). In addition to the WtP shown above in Table 1-3 we, therefore, have to consider the relevant costs. Prices are directly driven by variable or, more

precisely, marginal costs (MC), not by fixed costs. Fixed costs only influence the level of profits and are, thus, important for entry and exit of firms (which again indirectly affect prices).

59. The equilibrium end-user prices for all scenarios are shown in Table 1-4. While the first two scenarios consistently lead to the highest prices, the order of prices overall differs between the Hinterland and the No-Hinterland model. Because of product differentiation the incumbent's price may be below the entrants' price (for instance, in the GPON over P2P scenario) if the incumbent's variable costs are sufficiently lower to offset for quality and goodwill differences which tends to lead to a higher price. In the No-Hinterland model the equilibrium number of firms is in two cases one higher than in the Hinterland model. In both these cases the order of prices between Hinterland and No-Hinterland model is affected by this difference.

Table 1-4: Marginal costs (MC) and prices (p) in Euro per month

			Hinterland			No-Hinterland			
Scenario	$MC_{Iperceived}$	MC_E	n-1	p_I	p_E	n-2	p_I	p_E	p_C
P2P unbundling	34.36	36.22	3	46.32	44.87	4	42.07	42.37	23.76
GPON over P2P unbundling	32.22	36.22	3	44.71	44.72	3	43.58	45.54	27.92
WDM PON unbundling	33.37	34.00	4	42.46	38.69	4	41.24	39.32	26.16
GPON bitstream core	31.99	32.62	4	41.58	37.44	4	40.10	37.63	28.28
GPON bitstream MPoP	31.53	32.16	3	43.04	40.52	4	38.76	37.67	27.15

Index I: Incumbent, E: Entrant, C: Cable; n: number of operators

60. Retail prices are quite sensitive to the number of firms in the market, if the number of firms is small. Retail prices decrease with the number of firms in the market for all market players. The absolute price differences between incumbent and entrants increase slightly and the relative differences increase significantly in the number of firms. This suggests that entry increases competition among entrants by more than competition between the incumbent and entrants. Competition by cable brings prices of entrants and the incumbent much closer than competition without cable.

Results on profits

61. Table 1-5 gives profits for the basic model for both the Hinterland and the No-Hinterland case. It should be noted that entrants' profits are always reported per entrant.

Table 1-5: Profits in Million Euro (per month)

	Hinterland			No-Hinterland			
Scenario	n-1	$prof_I$	$prof_E$	n-2	$prof_I$	$prof_E$	$prof_C$
P2P unbundling	3	24.83	3.74	4	18.78	0.45	2.81
GPON over P2P unbundling	3	27.89	3.38	3	26.91	6.55*)	13.22
WDM PON unbundling	4	13.05	1.83	4	17.91	2.92	13.09
GPON bitstream core	4	23.71	1.54	4	13.22	2.07	23.72
GPON bitstream MPoP	3	23.60	4.40*)	4	10.00	0.31	17.86

*) With 4 entrants there is a very small loss for each entrant.

Because of its higher retail prices and lower costs the incumbent can persistently earn higher profits than the entrants. This result holds even if one corrects for his larger market share. Profits of cable follow largely the quality differentials to FTTH. The greater the differential the lower is cable's profits.

62. The influence of the number of entrants on profits differs somewhat from the entry effect on prices. The reason lies in wholesale profits. In the Hinterland model wholesale profits (because of the associated increase in overall output) increase in the number of firms, thereby increasing the difference between entrants' profits per firm and the incumbent's overall profits. In the No-Hinterland case the incumbent's wholesale profits are, because of the intervening effect of cable output, first increasing and then decreasing in the number of firms, resulting in a closing of the gap between entrants' profits per firm and the incumbent's overall profits. All firms experience a decline in profits per firm, as the number of firms increases. However, this happens at a declining rate, suggesting in particular that profits per entrant do not change dramatically around the free-entry equilibrium if the number of firms is fairly large.

Results on market shares

63. Table 1-6 provides market shares in the basic model. It should be noted that entrants' market shares are always per entrant.

Table 1-6: Market shares 's' in percent

	Hinterland			No-Hinterland			
Scenario	n-1	s_I	s_E	n-2	s_I	s_E	s_C
P2P unbundling	3	40.7	19.8	4	23.4	13.5	22.5
GPON over P2P unbundling	3	42.1	19.3	3	26.3	16.5	24.2
WDM PON unbundling	4	41.4	14.7	4	24.5	12.1	27.1
GPON bitstream core	4	43.4	14.1	4	24.8	11.0	31.1
GPON bitstream MPoP	3	41.5	19.5	4	22.6	12.1	28.9

In both models the incumbent's market share stays in a narrow range through all scenarios, although it varies more in the No-Hinterland model than in the Hinterland model. In the No-Hinterland model the market share of cable varies substantially. It closely follows quality differences between cable and FTTH and is lowest where the quality differential to FTTH is greatest.

Results on consumer surplus (CS) and welfare (W)

64. Table 1-7 summarizes our basic model results for CS and W. It also puts the results on prices, profits and market shares in perspective. In this context it needs to be noted that CS is largely driven by the price/valuation relationships between the different technologies and firms rather than by the overall quantity of output, which is fixed in the No-Hinterland model and varies only for each firm's backyard in the Hinterland model.

Table 1-7: Basic model results on consumer surplus and welfare per month

	Hinterland					No-Hinterland				
	n-1	CS		W		n-2	CS		W	
Scenario		Mio €	Rank	Mio €	Rank		Mio €	Rank	Mio €	Rank
P2P unbundling	3	243.1	2	279.2	2	4	466.9	1	490.3	2
GPON over P2P unbundling	3	245.6	1	283.6	1	3	434.0	2	493.8	1
WDM PON unbundling	4	240.5	3	270.8	3	4	431.2	3	473.9	3
GPON bitstream core	4	216.8	4	247.7	4.5	4	400.5	5	445.7	4.5
GPON bitstream MPoP	3	208.6	5	245.4	4.5	4	416.0	4	445.1	4.5

65. The ranking of CS in the Hinterland model is very close between the first three scenarios (with a 2% difference between GPON over P2P unbundling as the first and WDM PON unbundling as the third). In contrast, the difference between WDM PON unbundling as the third and the GPON bitstream scenarios is much larger (about 10%), while the latter two are almost equal. As explained below, the CS rankings are somewhat different in the No-Hinterland model and, except for the very close GPON over P2P unbundling and WDM PON unbundling cases in places 2 and 3, they are rather evenly spread.

66. In terms of W GPON over P2P unbundling ranks consistently first and narrowly beats P2P unbundling, while WDM PON unbundling is consistently third both for W and CS, usually with a significant margin. The margin is narrow for CS in the Hinterland model, because here WDM PON unbundling has 4 entrants, while the two P2P topologies only have 3 entrants. The two GPON bitstream scenarios are in a dead heat for last place in terms of W.

67. In contrast to CS, W is not much affected by entry, once the number of firms reaches 4 (No-Hinterland model) or 5 (Hinterland model). Thus, as a result of different numbers of entrants, the same rankings of W are as unsurprising as are different rankings of CS. While W first increases in the number of firms, this ebbs off very quickly and possibly starts to decrease. In contrast, CS continues to increase fairly strongly in the number of firms.

Level of wholesale charge

68. In our basic models we generally assume that wholesale access charges are determined according to the LRIC cost standard. Because of information asymmetries between the incumbent and the regulator identifying the proper level of the LRIC in a newly emerging network may be a difficult task. Furthermore, there is currently a policy debate on explicitly deviating from LRIC to incentivize FTTH investment. Under such concepts entrants have to pay a mark-up on the LRIC based wholesale access charge. We have tested the impact of such policies on competition and welfare on the basis of our modelling approaches.

69. Increasing the wholesale prices moderately by 10% has a significant impact on the critical market shares and the competitive coverage at the given ARPU. Only in the WDM PON scenario the profitable coverage of the competition model remains unaffected. The strongest effects occur in the P2P unbundling and GPON over P2P unbundling scenarios. The competitive business model here is only viable in Cluster 1 and 2. In the bitstream access scenarios the viability of competition is reduced from Cluster 5 to Cluster 4. The general increase in critical market shares indicates potentially a lower number of potential competitors and an increase in risk of market entry.

70. The oligopoly model shows less significant effects than the cost model. First of all, a percentage mark-up on access charges leads to an almost parallel increase of all retail prices (incumbent, entrants and cable). Therefore, the incumbent’s wholesale profits increase strongly and linearly. In contrast, the entrants profits and the incumbent’s downstream profits decrease very slightly with the mark-up. Cable’s profits are favourably affected. The market share of the incumbent remains more or less constant and the market share of cable increases at the expense of the share of entrants.

71. Welfare shows only a weak decline due to the mark-ups. Consumer surplus, however, shows a strong decline due to an increase in the access mark-up. Insofar as the number of competitors remains unaffected, the oligopoly model only shows limited effects on competition.

The effects of averaging

72. The cost modelling approach generally considers the investment decisions of the incumbent in a cluster-specific way. The investor decides for each individual cluster whether there is viability of investment on the basis of a given ARPU per customer. The profit maximizing firm will invest until the APRU exceeds costs in the marginal cluster. The infra-marginal clusters will generate a rent to the investor which may be used to expand coverage up to the cluster where the average cost over all profitable clusters still exceed ARPUs. We do not consider this case in this context.

73. In the competition model we have chosen a different approach. Our analysis here aggregates all variables and all results over the four densest population clusters of Euroland. This is based on the critical market share results of the cost model, which suggested that entrants and incumbents would be viable for all scenarios up to Cluster 4. This does not mean, however, that the viability of all firms, which was the basis of the free-entry equilibria presented so far, also holds for Cluster 4 in isolation. It may be doubtful because access charges, costs and end-user pricing have all been based on an aggregate (or average) of all four clusters. Cluster 4 as the marginal cluster with the lowest population density has higher fixed costs per user for all types of firms than the average of Clusters 1 to 4.

74. As a separate market, Cluster 4 would have about 24% the size of all four clusters. Under the averaged access charge for all four clusters we get the same prices as before, but in the Hinterland model profits of the incumbent are only about 10% of the aggregate profits and profits of the entrants are only 18%. However, Cluster 4 remains profitable in isolation so that the equilibrium number of firms is reemphasized. One drawback for the incumbent is that wholesale access becomes a major loss maker and offering wholesale access therefore is not incentive compatible. In contrast, incumbent's profits are only 6% of aggregate Clusters 1-4 profits and profits of entrants turn slightly negative in the No-Hinterland model. Thus, entrants may refrain from entering Cluster 4 in this case. Under cluster-specific wholesale access charges instead of an average access charge end-user prices increase but that only helps the incumbent, while entrants' profits/losses deteriorate.

75. Profits in the marginal Cluster 4 are substantially lower than average profits for all Clusters 1-4. Because of large losses from selling wholesale access profits overall can turn negative for the incumbent and slightly negative for entrants, suggesting that the incumbent may refrain from entering Cluster 4 and fewer competitors may enter the marginal cluster than the others. This latter effect on competitors becomes stronger if one uses cluster-specific entry charges or if the incumbent also enters Cluster 5.

Sensitivity of Greenfield approach

76. We have also studied the impacts of the lower investment costs of the Brownfield assumptions as presented in para. 24 to 29 on competition and welfare. The cost change from a Greenfield to a Brownfield model only concerns the capital costs of FTTH for the incumbent. Since this does not affect LRIC and therefore LRIC access charges are unchanged, the effect of the Brownfield model leaves end-user prices and market shares unchanged. Only the incumbent's profit is increased by the cost saving. This is a well-known result from the theoretical literature. The only effect of moving from Greenfield to Brownfield is that the incumbent's wholesale profits increase precisely by the cost difference between the Greenfield and Brownfield models.

77. If access charges are reduced by the cost savings of the incumbent end-user prices are reduced, market shares change little, profits of the incumbent are slightly reduced but those of entrants increase (compared to the Greenfield approach). If wholesale access charges are adjusted downward by the cost savings the end-user prices are lowered and profits for entrants increase. The incumbent's profits are substantially lower than under LRIC access charges but still somewhat higher than under the Greenfield costs. Welfare increases almost exactly by the cost savings. Most of this increase benefits consumer surplus but some also goes to profits.

Sensitivity on QoS and WtP assumptions

78. We have run several sensitivities to identify the impact of our QoS and willingness to pay assumptions on the results. Changes in the WtP assumptions can have substantial effects on the model results:

- A smaller spread between the different WtP for incumbents, entrants and cable shows that end-user prices, profits and market shares of the incumbent all generally decrease, while these variables increase for the entrants.
- Increasing the goodwill advantages of the incumbent increases end-user prices, profits and market shares of the incumbent at the expense of those of entrants. This result shows that the incumbent can have strong incentives to deteriorate the quality of the wholesale product provided to entrants.
- An improved WtP for WDM PON leads to entry of an additional firm, implying substantially lower prices and profits.
- An increase in the incumbency advantage leaves the rankings with respect to CS and W largely intact. CS and W generally decrease because of the lower WtP for entrants and cable services.
- An improved WtP for WDM PON changes the ranking of the scenario by moving it ahead of P2P unbundling and GPON over P2P unbundling.

2 Competitive models in fibre deployment

2.1 Introduction

The task of the competition model is to develop a steady-state model of competition in an FTTH oligopoly to show and to allow comparing end-user prices, consumer surplus and producer surplus (for both network owner and other firms). The following five scenarios of NGA technology and associated wholesale access seekers are considered (the costs of these have been derived from the cost model).[11]

1. (Ethernet) P2P unbundling: The incumbent builds a passive P2P plant and operates dedicated Ethernet P2P access lines. The competitors buy unbundled access at the MPoP level. In addition to the unbundling charge they have to collocate at the MPoP, invest in a small ODF of their own and Ethernet Switches as well as bear the cost of concentration and core network.

2. GPON over P2P unbundling: The incumbent builds a passive P2P plant but contrary to the previous scenario deploys GPON active electronics and splitters at the MPoP for his own operations. Competitors buy unbundled access in the same fashion as in the first scenario.

3. WDM PON unbundling: The incumbent builds a passive Point-to-Multipoint plant that has cascaded splitters at the distribution point and MDF level. The majority of MDF locations is closed and about 500.000 lines are concentrated in MPoPs with WDM PON technology. Competitors buy "unbundled wavelength access" to individual customers. Because of the high level of concentration realised through MDF dismantling competitors only add their own core network; no further concentration is required.

4. GPON bitstream access

    a. at the core network level: The incumbent builds a passive Point-to-Multipoint plant with passive splitters at the distribution point and operates active GPON electronics at the MPoP. He provides bitstream access to competitors at the core level so the bitstream includes a transport service through the incumbent's concentration network. Competitors collocate at the incumbent's first level core location nodes and add their own core network.

11 One has to differentiate between topologies (Point-to-Point, Point-to-Multipoint) and the active layer 2 technologies used to light the fibres (Ethernet, GPON). Throughout most parts of this study we use the term P2P to refer to the combination of Ethernet technology and P2P topology. In some case we may want to exclusively refer to the topology. In this case we would e.g. speak of P2P topologies which would include the first two scenarios.

b. at the MPoP level: The incumbent builds a passive Point-to-Multipoint plant with passive splitters at the distribution point and operates active GPON electronics at the MPoP. He provides bitstream access to competitors at the MPoP level so competitors have to provide their own concentration and core network.

Accordingly, scenarios differ by FTTH access technologies and by the mode of access provided to competitors (= entrants). Table 2-1 describes the scenarios in terms of the value added supplied by the incumbent to entrants. The scenarios are described in detail in section 2.3.

Table 2-1: Costs borne as access charge (ULL, bitstream access charge) by entrants by scenario (shaded)

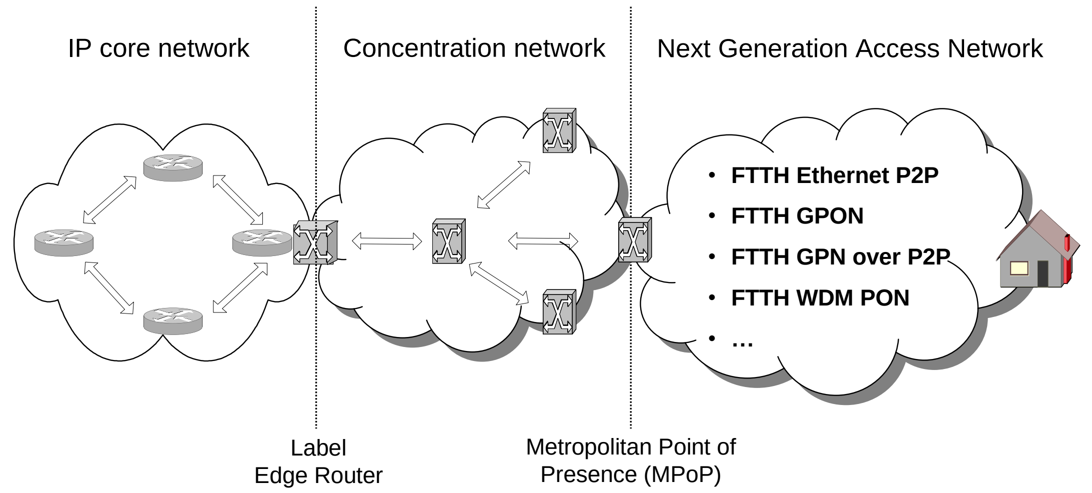
Entrant costs scenario	FTTH access network	MPoP electronics	Concentration network	Core network	Retail
P2P unbundling					
GPON over P2P unbundling					
WDM PON unbundling					
GPON bitstream core					
GPON bitstream MPoP					

Since we regard subscriptions as the units of sales, ULL and bitstream access in our approach only differ by costs, wholesale prices and QoS, but not by units of measurement. This allows us to use the same formal model for all scenarios; we only need to adjust parameter values appropriately.

2.2 The overall NGN/NGA architecture

Next Generation Networks allow one to transport many different application contents over one universal IP-protocol based electronic communication network. Such content may be data, voice-telephony or TV/video etc. The new approach of NGN networks is that all this content is transported and switched within one single network, while in the past different networks of different technologies have been used at the switching level. The universal transport protocol used is the Internet Protocol (IP). Integrating all electronic communication content into one single network and taking into account the increasing demand of electronic communication/usage of electronic applications requires overcoming bandwidth bottlenecks in the access networks. The new access networks are therefore based on fibre access lines, which either shorten the existing copper lines or even replace them totally in the FTTH architectures.

Figure 2-1: NGN/NGA general architecture



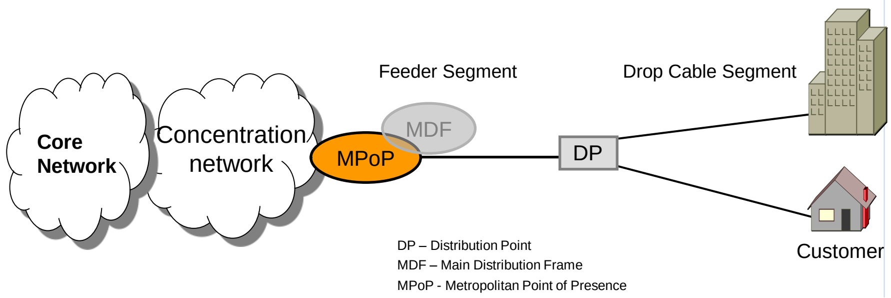
The overall NGN/NGA architecture has three major segments, the IP core network, the nowadays typically Ethernet based concentration network and the access network. In the IP core network the IP-traffic is switched between end users or connected to the application servers located in the core layer locations or in other networks. The concentration network collects the traffic from the endpoints of the access network and transports and concentrates it to the core network nodes. The access network of today is based on copper lines between the Main Distribution Frame (MDF) locations and the end customer locations. Their replacement by fibre lines has already started. Many different technologies are available and implemented. Before we describe them we define some general access network related terminology used in this study.

Regarding access network topology we use the terms of the European Commission's NGA recommendation.[12] It defines the Metropolitan Point of Presence (MPoP) as equivalent to the Main Distribution Frame (MDF). The MPoP is the last location where, depending on the NGA architectures and looking from the end user, an Ethernet Switch of the concentration network is located. The Distribution Point is an intermediate node in the NGA, from which fibres from the MPoP can be divided/accessed before running them to the customer building (or in the case of FTTC from which access is realised through copper sub loops). The segment from MPoP to Distribution Point is called Feeder (Cable) Segment. The segment from Distribution Point to the customer location we call Drop (Cable) Segment[13]. There may be fewer MPoPs than MDFs, since fibre overcomes the line length restrictions of copper connections. Thus MPoPs may be a

12 European Commission (2010).
13 The EU NGA Recommendation (2010) calls this network segment terminating segment also, but for reasons of consistency with recent WIK studies we continue to use the term drop cable segment in this study. Both terminologies characterise the same network element.

subset of the existing MDFs. In this case we will use the term “backhaul” to refer to the segment between an abandoned MDF location and the new MPoP.

Figure 2-2: Network topology: Terms and definitions



There are three general approaches to reduce the copper line length in the access network, Fibre to the Curb (FTTC), Fibre to the Building (FTTB) and Fibre to the Home (FTTH). With FTTC there are fibre lines between the MPoP and the Distribution Point (DP - a street cabinet) only. The DP hosts electronic (VDSL) equipment which transmits the broadband signal over the existing copper pairs between the DP and the end user homes. With FTTB the fibre lines cover the distance between MPoP and end customer buildings, where electronic equipment in the basement of the building transmits the broadband signals, using the existing inhouse copper cabling, to the end customer home (e.g. apartment). With FTTH all the distance between MPoP and end customer home is bridged by fibre lines. Here no remaining copper segments reduce the bandwidth. In single dwelling buildings FTTB and FTTH fall together, while in multi dwelling buildings FTTH requires a fibre inhouse infrastructure which also has to be deployed during fibre roll out.

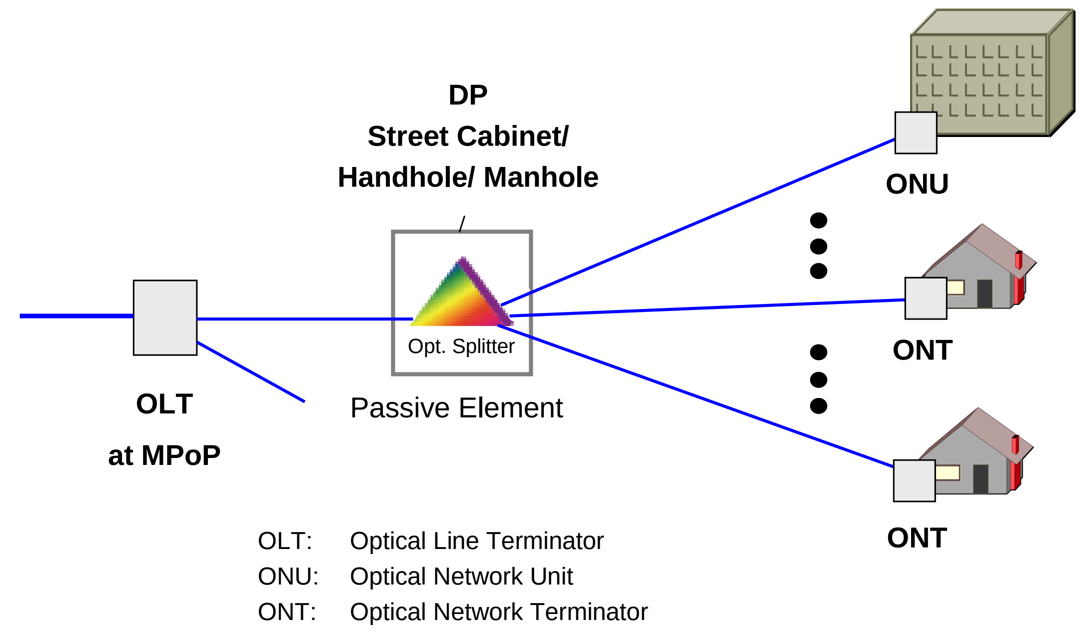
FTTC requires the lowest number of new fibre lines. The number of fibres depends on the degree of concentration a DSLAM in the DP (street cabinet) provides, e.g. on the amount of user interfaces a single DSLAM offers. Typical values are below 1000 users per DSLAM. Fibres are then only installed in the feeder segment.

FTTB requires one fibre per building in the feeder and in the drop cable segment. Thus the degree of fibre concentration is driven by the number of homes per building, or by the number of FTTB-terminating systems (called ONU, Optical Network Unit) in the case of large multi dwelling units, depending on the system’s user port capacity. A typical figure for the latter may be 8.

FTTH Point-to-Point (P2P) requires one fibre per home in both, the feeder and the drop cable segment, and in the inhouse cable segment, too. Thus FTTH is the architecture with the highest fibre count in the feeder cable segment, which may cause cost differences.

Point-to-Multipoint Passive Optical Network (PON) technology concentrates the optical signals of several fibres onto one single fibre by a passive component called splitter (Figure 2-3). This architecture thus reduces the number of fibres in the feeder segment compared to the Point-to-Point fibre architecture described above. The degree of fibre reduction depends on the splitting factor a splitter supports[14]. Only one fibre per splitter is needed between MPoP and splitter location (e.g. a DP). However, one fibre per home (FTTH) or per building (FTTB) is still required in the drop segment. Accordingly the drop cable segment in PON architecture has the same fibre count as a P2P architecture.

Figure 2-3: Point-to-Multipoint fibre architecture



Due to the fact that multiple end customers can send their upstream information at the same time some administration is necessary in order to manage conflicts and also in order to manage the downstream traffic. The systems used for this are the Optical Line Terminators (OLT) at the central site and Optical Network Units (ONU) for several end customers (e.g. FTTB) or Optical Network Terminators (ONT) for one single end customer (e.g. FTTH). All customers connected to the same splitter share the same communication channel and its bandwidth. There are many different PON systems. The

14 A splitter spreads the optical downstream signal onto many fibres and in this way distributes the power of the downstream beam also. Therefore the splitting factor not only is limited by construction constraints, but by the total optical budget of the system, too. Typically current splitting factors are between 8 and 32.

most commonly one used in Europe, GPON, is considered in this study and our models. PON systems (MPoP equipment and customer modems) have to interact and be compatible; in order to fully support all functionalities PON components often have to be from the same supplier.

Another, more advanced Point-to-Multipoint fibre technology is under development, which allows one to use different colours (optical wavelengths) of the optical signal to address different customers over a single fibre. The technology of using different colours to separate individual communication streams on a single fibre is called Wave Division Multiplex (WDM). While the fibre plant does not differ compared to PON, the WDM-splitters need not necessarily distribute all colours to all end customers, but may be configured to provide individual colours to each of the end customers.[15] Each end customer may then use its own colour beam individually, not sharing its bandwidth with the neighbours at the same splitter.

Wholesale access for competing operators may occur for all NGA architectures in two different manners, by accessing the physical infrastructure to the end customers or by obtaining access to a bitstream which is managed by the wholeseller.

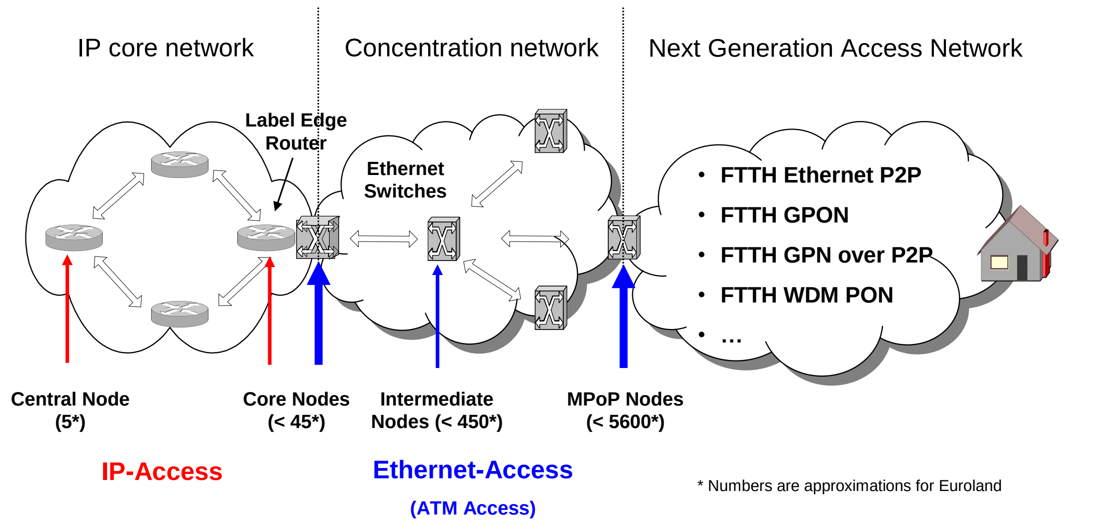
In FTTH architectures based on a Point-to-Point fibre plant, a physical access to the fibre access lines occurs at the MPoP, where all access lines are concentrated at the Optical Distribution Frame (ODF) and where the competitors may collocate their own equipment. This is very closely comparable to the well-known copper Local Loop Unbundling with all its proven processes and skills. In Point-to-Multipoint fibre plants the fibre star point is at the splitter site, thus the competitors have to collocate there – with accessible cabinets and Optical Street Distribution Frames (OSDF), making these locations significantly more expensive. In cases of cascaded splitters it is the splitter location closest to the end customer locations where unbundling would take place. The closer the splitter location to the end customer, the more locations are needed and the more expensive the own infrastructure of the competitors will become. In addition, the less customers are concentrated per splitter and the less customers a competitor can therefore acquire per location, the less attractive it is for competitors to collocate there. The dispute of the optimal splitter location is well known from the French discussion about the optimal mutualisation point. Studies by WIK-Consult and others have demonstrated the unattractiveness of Sub-loop Unbundling at the DP[16] compared to Local Loop Unbundling at the MPoP. In our ongoing considerations we will therefore not consider the physical unbundling at the DP.

For all NGA architectures there are many points for active electronic interfaces to access connections to the end customers (Figure 2-4) at all network node locations of the concentration and core network. At the concentration network the interfaces are typical-

15 This in general improves the optical budget and the length over which the signals can be transmitted.
16 See e.g. Elixmann/Ilic/Neumann/Plückebaum (2008), Ilic/Neumann/Plückebaum (2009), Ilic/Neumann/Plückebaum (2010), Analysys (2007).

ly based on the Ethernet protocol, and the state of the art equipment also consists of Ethernet switches[17]. In the core network IP routers operate offering IP interfaces for wholesale access. [18]

Figure 2-4: Access point options for wholesale bitstream access (WBA)



A bitstream access at the core network nodes aggregates many customers at one Point of Interconnection (PoI), whose traffic may be influenced by the traffic of the other customers of the wholesale operator and by the traffic of the other customers on the network. The closer the PoI is relative to the end customers, the less customers are aggregated and the less the traffic is influenced by the wholeseller's own operations and network management.

Beside that a PoI at the MPoP level may also allow for bundled interfaces for a group of end customers without any overbooking/concentrating the end customers' access bandwidth, thus forming a so called Virtual Unbundled Local Access (VULA).[19] Such concepts are well known from the bundled local loop access lines in the FTTC/OPAL[20] areas of Germany since 1998. While the OPAL bundled access uses ITU-T V 5.1[21] like interfaces, the VULA is based on Ethernet. In these access concepts the competitor still relies on some last active access nodes of the wholeseller, which have to be config-

17 The older ATM equipment is also mentioned in Figure 2-4.
18 With FTTC architectures and DSLAMs at the DP one could also in theory imagine a bitstream access at the DP site, requiring the competitors to collocate there, which we do not consider under the same reasoning as for the physical unbundling approaches.
19 See article 7 notification responses of the EU Commission to UK (EU Commission (2010b)) and Austria (press release IP 10/10/760) as well as the decisions of the Austrian Telekom-Control-Kommission TKK (2010a) und TKK (2010b), all from summer 2010.
20 Optical Access Line.
21 PSTN E1 interfaces with 30 user and 2 control channels with 64 kbit/s each.

ured, operated and repaired by him and still form a procedural hurdle for a clear and transparent network provisioning and operation of the competitor. Even with future WDM PON, where the customer access connections may be handed over to the competitor as colour beams on a single fibre, the competitors' network quality will depend on the wholeseller's quality to provide and operate the WDM access nodes. Thus, even the so called Lambda[22] or Wavelength Unbundling is a low layer but active wholesale access.[23]

Nevertheless, in Point-to-Multipoint fibre plants the VULA may be the highest quality wholesale customer access a competitor can buy. Compared to unbundled fibres customer access bandwidth above the wholesale bandwidth or own products based itself on WDM technology could not be offered by a competitor using WBA, VULA or Wavelength Unbundling.[24]

2.3 Technologies/architectures considered[25]

Constructing new broadband access networks should be done in a way which will satisfy the end customer demand for almost the estimated life time of the components, e.g. the fibre lines. This is significantly long and will exceed 20 years. Thus the architectures considered should at least cover future demand right now or should have a proven migration path for significant bandwidth upgrade.

The future bandwidth needs of a residential customer at the upper end are uncertain (50 or more than 100 Mbps symmetrical, or even more could be conceivable). For business and even more for wholesale customers we already now see high bandwidth demand, which cannot be satisfied by all NGA architectures. So already today mobile base stations could require more than 100 Mbps backhaul line capacity and an increasing number of business and wholesale customers need direct fibre access and exploit a major share of the optical frequency spectrum (e.g. with CWDM, Coarse WDM or even DWDM (Dense WDM)). The ideal future NGA architecture can cover all customer access demand or at least allows one to do so with small enhancements.

In this study we therefore consider those NGA architectures which allow for highest bandwidth and quality for the end customers and which do no longer rely on copper cable elements. These are FTTH architectures only. From all FTTH architectures we concentrate on the two most relevant architectures in Europe, Ethernet Point-to-Point

22 Lambda stands for wavelength of light and is equivalent to light of a dedicated colour.

23 We do not enter into the discussion if VULA and wavelength unbundling should be considered in the market 4 or 5. From the point of network operation and related product quality it is only relevant that there is active equipment in the customer access line – in the value chain – which is not operated by the competitor and thus influences/hinders transparent customer provisioning and network operation, restricts product definition and requires process interfaces in a degree, which would not be needed if only physical wholesale products would be used in the value chain.

24 It is of course questionable if such products are relevant today or in the future, throughout the lifetime of the NGA architecture.

25 In Annex 2 we describe those technologies which we do not consider in this study.

and GPON. In order to overcome some restrictions and weaknesses being discussed for GPON we also include into our considerations two GPON variants, one implementing GPON electronics on top of a passive Point-to-Point fibre plant and a future version of PON, increasing the bandwidth and quality of the nowadays PON systems by using WDM technology on a Point-to-Multipoint fibre topology. All architectures considered will be described with their relevant characteristics for product definition and cost in the next sections.

In the discussion on the relative performance of Ethernet P2P and GPON technology arguments about different OPEX, especially concerning space requirement and power consumption, have been exchanged. Therefore we model the space requirement and the power consumption of the architectures considered explicitly in a bottom-up manner. For the size of an MPoP we assume, that the equipment to serve fibre lines for 100% of the homes passed has to be hosted. For Point-to-Multipoint topologies all fibres are connected to OLTs, in the case of P2P topologies the floorspace dimensioning for active equipment is based on 70% take-up[26] (see sections 3.1.1 on the fixed network market reach and 3.1.6.2 on floorspace issues).

In our model we assume that the incumbent is the investor of the NGA network infrastructure. Competitors (new entrants) face the same (efficient) cost if they provide access on the basis of wholesale access to the incumbent's network, but may achieve a lower ARPU. If the NGA architecture is based on a Point-to-Point fibre plant we consider the competitors to use unbundled fibre loops as wholesale access service in this study. If the architecture is based on a Point-to-Multipoint fibre plant, we consider an active wholesale access at the MPoP or at the core network node locations.

In total we consider the following architectures (Table 2-2). Details of the architectures are explained in the next subsections in the order Ethernet P2P, GPON, GPON over P2P as a special implementation and WDM PON.

Table 2-2: Overview of the architecture scenarios considered

Scenario	Incumbent architecture	Competitor (Entrant) wholesale base
P2P unbundling	Ethernet P2P	Fibre LLU at MPoP
GPON over P2P unbundling	GPON over P2P	Fibre LLU at MPoP
WDM PON unbundling	WDM PON	WDM unbundling at Core Nodes
GPON bitstream core	GPON	Bitstream access at Core Nodes
GPON bitstream MPoP	GPON	Bitstream access at the MPoP

26 We expect a long-term market of the FTTH network of all potential access lines in the competition against cable, mobile and non-users.

2.3.1 P2P

FTTH Point-to-Point (P2P) deploys fibre access lines from the MPoP to each of the customers' homes (apartments, dwellings). The complete fibre capacity is available for each customer in the subscriber access network since every customer has a dedicated fibre from his home to the MPoP, thus one fibre per home in both the feeder and the drop cable segment is required. Because of the uncertainties of the future bandwidth need of residential and business customers this Point-to-Point fibre plant appears to be the most future proof solution, because the use of the full optical spectrum per fibre is not restricted by any intermediate technology.

The maximum length a fibre local loop may have is determined by the optical budget of the fibre connection and the power of the interface cards at the MPoP and end customer location (respectively their lasers and receivers). Without intermediate repeaters today's interface cards may reach up to 40 - 80 km. But the longer the distance bridged, the more expensive the interfaces will become. In NGA networks we talk about mass market deployments, thus expensive interface cards could have a significant impact on total cost. In our model assumptions for Ethernet P2P we therefore take the same line length assumptions as for the copper access network.

Another discussion covers the manageability of larger fibre network starpoints, so that an upper limit regarding the fibre count at the MPoP might exist. Today large copper MDFs serve more than 35,000 copper pairs. With fibre an end customer connection in Point-to-Point fibre plants needs only a single fibre instead of a copper pair and each fibre requires less space (has a much smaller diameter) than a copper wire. The Optical Distribution Frame may be larger than the copper equivalent, so the ODF may still be a little bit larger per fibre, but due to technical innovations this may change over time. Overall, a fibre MPoP will be able to serve more fibre links than the largest copper MDFs today. Therefore, we are convinced that with our model approach of assuming the existing copper MDF locations to be the proper scorched nodes of the new NGA network, where all existing spare ducts may be used, we are conservative and do not raise fibre management problems.

In the P2P architecture the incumbent terminates the access fibres on an Optical Distribution Frame located in each of the MPoPs. Thus an ODF has as many customer sided ports as potential customers are in the field and as many homes have been passed by the fibre plant. The ODF is used to connect the single fibres to the ports of the traffic concentrating Ethernet equipment by patching only the access fibres of the subscribers to the network sided ports of the ODF, which then are connected to the ports of the Ethernet switches. This arrangement also allows one to connect each end customer individually to ports of different speed (0.1 to 10 Gbps) or to separate dedicated equipment.

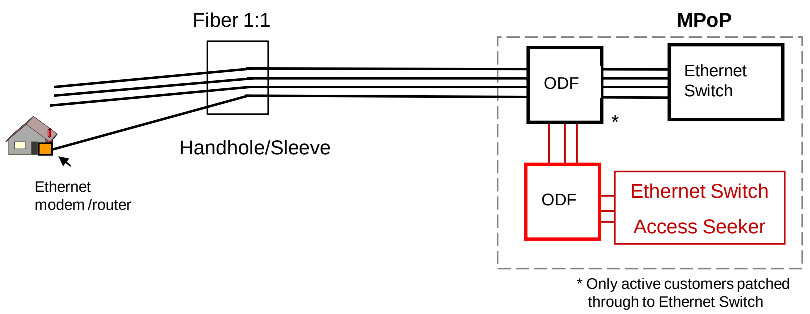
If more than one Ethernet switch is needed to connect the active customers additional switches are considered in a cascaded and hierarchical manner. The last network sided switch then is the border to the upper concentration network. The network sided interface cards are already part of the concentration network. They are considered separately in the respective cost calculations in order to adapt to the wholesale cost calculations (see below).

For competitors using wholesale access we have considered a fibre unbundling scenario for the P2P architecture in which a competitor rents the unbundled fibre loop, places an additional Optical Distribution Frame of his own at rented collocation space in the MPoP where he operates his own Ethernet Switch. The competitor's ODF is connected via a dedicated connection cable to dedicated customer sided ports of the incumbent's main ODF. The costs of all these elements are part of the competitor's total cost. In addition, the competitor has to bear the cost of the concentration and core network himself.

Figure 2-5 not only describes the P2P topology in general and which cost elements are considered in the incumbent's total cost, but also details which cost items become part of the fibre LLU price (underscored cost positions) and which elements and costs of the access network the competitor has to bear directly (red).

We treat the incumbent deploying a P2P network and offering fibre unbundling to competitors as our first scenario.

Figure 2-5: Scenario P2P with fibre LLU



Incumbent cost (relevant for LLU price)
- CPE
- Access Network incl. Inhouse cabling
- ODF + Patch cabling + floorspace
- Ethernet Switch + floorspace + energy
- Network sided Ethernet port (1 per MPoP)

- Concentration Network
- Core Network

Competitor cost**
- CPE
- LLU charge
- Competitor's ODF & Patch cabling + floorspace
- Ethernet Switch + floorspace + energy
- Network sided Ethernet port (1 per MPoP)

- Concentration Network
- Core Network

** Assumption: Unbundler operates Ethernet P2P network

2.3.2 GPON

The GPON technology is designed to deal ideally with Point-to-Multipoint fibre plants. It concentrates the traffic of a significant number of customer access fibres at an intermediate optical splitter location (DP) onto a single backhaul fibre. Optical splitters may be cascaded in order to optimize the fiber count and to adapt it to the end customer distribution. But each splitter adds some additional attenuation by getting spliced into the cable and because it has to distribute the power of the downstream signal to all fibres connected. Thus the fibre plant strongly depends on the optical power budget and the maximum splitting factor. ITU-T G.984 standardises GPON in its limitation of 20 km reach at a 1:32 maximum splitting factor. New standards and better interfaces allow a splitting factor of up to 64 or even 128. For our models we assume a splitting factor of 1:64 under any circumstances in a single step, without any cascades.

Already in order to enable the use of existing spare ducts we assume DP locations and sizes comparable to an efficient copper plant. These may host several splitters, according to fibre count.

In our incumbent model the fibre plant is deployed to all homes (100% homes passed). This assumption corresponds to an efficient fibre deployment strategy. The fibres are connected to splitters filling them up to 90% of their capacity, keeping spares for future use and additional capacity. The fibres from the splitters are connected to the client side of the ODF in the MPoP, patched over there to the appropriate OLTs. The OLTs are connected to an Ethernet switch which is the interface to the concentration network. Especially during ramp-up when only few potential customers have already become subscribers to the FTTH network this architecture still has considerable spare capacity, which will be reduced as the take-up increases.

Keeping the copper MDF locations as scorched nodes where the existing duct plant concentrates we are confident that fibre management problems at the MPoP sites due to the number of fibres will never occur, since the fibre count in the feeder cable segment is reduced by the splitting factor compared to a P2P approach. The fibre count in the drop cable segment between (the last) splitter and the end customer premise will be the same as in the P2P case.

In order to coordinate communication of users with the active electronics at the MPoP, admission rights are administered by a central component (the Optical Line Terminator – OLT) which has to interact with decentralised components at the end customer sites, called ONU (Optical Network Unit, in case of several customers) or ONT (Optical Network Terminal, in case of one customer). Accordingly, OLT and ONU/ONT must be able to communicate with each other. International standards generally only offer a basic, minimal level of interoperability, thus in practice there is a supplier dependency between OLTs and ONUs/ONTs. By contrast, the degree of supplier dependency for P2P solutions is not significant, because current solutions for active equipment are all based on standard Ethernet interfaces that interoperate in a worldwide mass market.

GPON systems offer a downstream bandwidth of 2.5 Gbps and an upstream bandwidth of 1.25 Gbps, shared between all customers connected to the same splitter (respectively splitter chain) or OLT port. In the case of 64 end customers per splitter it would result in approximately 40 Mbps down- and 20 Mbps upstream per customer as a fixed capacity, which can be used in a shared manner if the system is configured appropriately, so that the users may achieve the total sum of bandwidth as a peak capacity. Also if the splitters are not completely filled with active subscribers the spare capacity may be shared between the subscribers.

GPON with its central administration of sending rights in the OLT in principle allows one to allocate a fixed bandwidth or more dynamic bandwidth for an end customer and thus enables to serve end customers in an individual manner. But this is limited to the degree the other customers are not harmed or restricted in their principle capacity demand. Reducing the amount of customers connected to a splitter is another method to increase bandwidth per customer, and of course both methods may be combined. But reducing the amount of customers for a splitter requires a change in the fibre plant. Since customer demand cannot be planned in advance, some spare splitters could be foreseen during fibre roll out for future use.

All fibres will be driven by the same interface cards, so individual solutions to single, dedicated (business or wholesale) customers going beyond Ethernet interfaces above 1 Gbps or requiring access to the optical spectrum (WDM band) cannot be supported by GPON, but may require additional fibres in the feeder and drop cable segment.[27] Additional spare splitters or fibres are not considered in our model assumptions, because we did only model pure architectures and no hybrid solutions.

Each ONU/ONT has to listen to the downstream messages of all connected customers and filter them for its own end-user. The downstream messages are encrypted, but may be listened to by all neighbours at the same splitter. This inherently makes the system more vulnerable to illegal interception and/or generates higher costs for encryption to secure communications. The upstream messages between end customer and OLT are not encrypted and may be reflected by imperfect splices in the feeder cable, thus enabling clear text interception with very sensitive (special) receivers. Denial of service attacks may be started with a strong optical beam ignoring the OLT's administration, or by affecting the OLT's administration messages, and there is also a certain risk that faults in one ONU/ONT may affect all the other endpoints of the same splitter/OLT. Determination of fault locations in such a spread environment is harder to achieve than in a P2P system where only single lines fail under these circumstances. Thus we assume GPON systems to be more vulnerable to illegal interception, denial of service attacks and un-

27 With sub-loop access at the DP and an OSDF additional feeder fibres could be flexibly connected to the drop segment without any additional fibre count.

der certain fault conditions more time consuming to repair. We will consider this aspect in our assumptions about quality differences in our competition model (section 2.6.1.3).

GPON architectures concentrate the traffic onto fewer electronic interfaces at the Central Office. These active components are more complex and more expensive than P2P components. The same holds true for end user devices. As long as a GPON architecture cannot make use of the concentration of the splitters, because users have not yet subscribed or infill homes[28] are not yet constructed, many splitter locations in an OLT are likely to stand empty for a significant period of time. This situation could be improved with intermediate distribution frames at splitter locations. Nevertheless, this complexity does not occur with P2P architectures, where ports are only installed and operated to connect active customers.

GPON architectures are well suited to asymmetric traffic, inasmuch upstream and downstream bandwidth differs due to the inherent upstream communication collision. A preponderance of downstream traffic over upstream has so far been a typical residential communication behaviour, and GPON is well suited to residential customers who have substantial downstream and limited upstream communication demand. However, already today business customer demand is symmetrical. And even for residential customers, there is a strong progressive trend towards more symmetric broadband communication (e.g. video conferences/telephony, gaming, Peer-to-Peer[29] communication). Therefore, one might question whether the GPON architectures are really future proof in the long-term concerning traffic patterns, given that fibre-based infrastructures could have economic lifetimes of as much as 40 years.

If GPON had to deal with a bandwidth demand increase by a factor of 10, then the planned GPON evolution to 10G-PON would not suffice; however, one can be confident that new GPON technologies will appear, or that the installed Point-to-Multipoint fibre plant may be used to migrate to WDM PON.[30] Migration to systems where the optical frequencies used overlap each other (e.g. GPON and DWDM) require the complete exchange of the components in the fibre strings (tree) of a splitter/OLT in one step with all ONU connected (e.g. 64) or a redesign of the fibre plant. Migration to technologies requiring a Point-to-Point fibre plant would require additional ducts and fibres in the feeder cable segment, thus should be avoided if possible.

GPON, deployed with splitters in the field, can at present only be unbundled at the splitter locations closest to the end customers. Fibre sub-loop unbundling is not considered in this study as it does not appear to be a sufficiently profitable wholesale product. In-

28 Homes which may be constructed later.

29 Peer-to-Peer is in many cases also referred to P2P. In this study we only use the term P2P for the fibre architecture, not for the logical communication relation in the layers above.

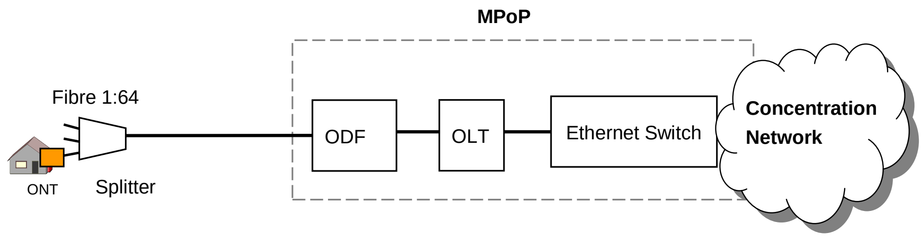
30 For migration from GPON to 10GPON the optical windows of the frequency plan are synchronized and allow for overlay installations and smooth migration. With XG-PON2 of FSAN (Full Service Access Network, the member companies drive standards into products and contribute to the standardization process via ITU-T) 10GPON will offer 10 Gbps symmetrical shared bandwidth. From 10GPON to WDM PON overlay and frequency plans are not coordinated and will cause conflicts (Figure 2-9).

stead we consider two bitstream access scenarios in the GPON case, bitstream access at the core network level and at the MPoP level for the competitors' wholesale access cases. The main difference between the two scenarios is that bitstream access at the core level includes the transport through the incumbent's concentration network while in the other bitstream scenario the competitor has to use his own concentration network and may obtain a transparent, non-overbooked bandwidth from the MPoP to his end customers, resulting in higher product quality and the ability of independent product design compared to the GPON bitstream core scenario. But since the competitor still depends on the incumbent's active components this quality improvement will not achieve the degree of unbundled fibre local loops.

Since the incumbent benefits more from economies of scale his unit cost of the concentration network transport will be lower than that of the competitor, thus the competitor in the GPON bitstream core scenario may benefit from the lower cost in the wholesale price.

Figure 2-6 and Figure 2-7 show the GPON architecture and detail cost components for the two scenarios. The underlined cost components once again are the input for the wholesale price calculation, while the components in black build the total cost of the incumbent and those in red the total cost of the competitor.

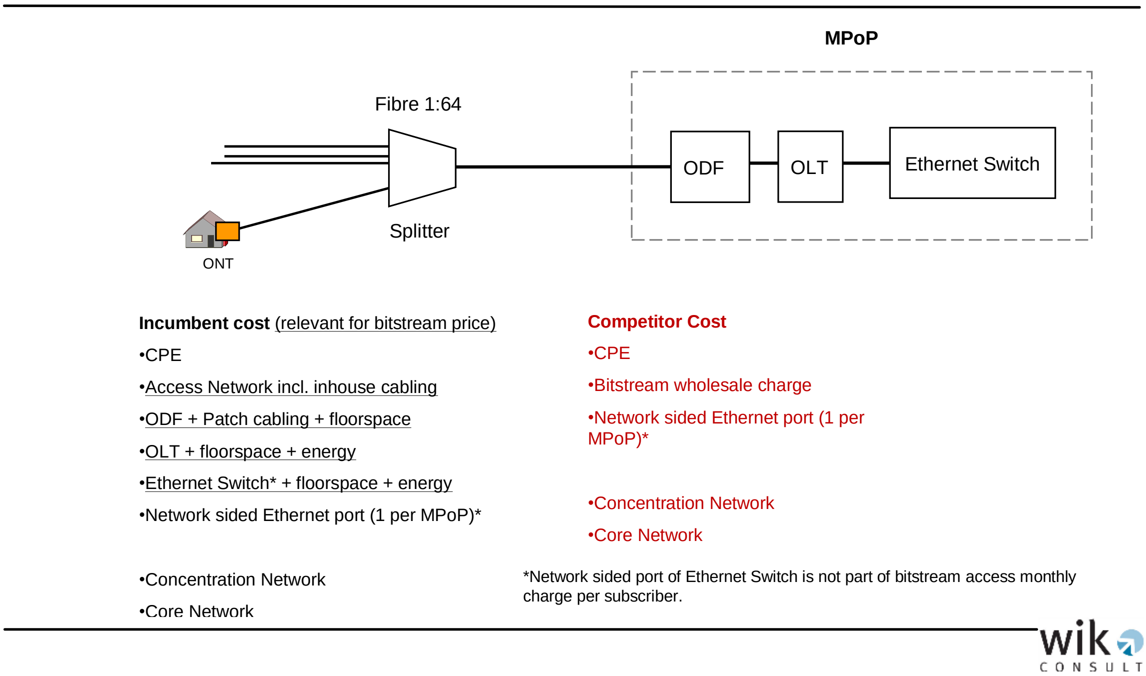
Figure 2-6: Scenario GPON with bitstream access at the core level



Incumbent cost (relevant for bitstream price)
- •CPE
- •Access Network incl. inhouse cabling
- •ODF + Patch cabling + floorspace
- •OLT + floorspace + energy
- •Ethernet Switch + floorspace + energy
- •Concentration Network
- •Core Network

Competitor cost
- •CPE
- •Bitstream wholesale charge
- •Network sided Ethernet port (1 per MPoP)
- •Core network

Figure 2-7: Scenario GPON with bitstream access at the MPoP level



Most GPON systems allow one to distribute a separate cable-TV signal (RF signal)[31] as a separate wavelength in a broadcast manner from OLT to ONU/ONT. This signal is terminated on a coax plug and can be fed into the existing cable-TV cabling at the end customer homes. If enough bandwidth is set aside for the RF signal (e.g. 2.5 GHz bandwidth of this additional RF signal) the RF channel may be shared between several cable-TV signals (e.g. 3 x 800 MHz) and thus is open for unbundling and wholesale offers also. This feature adds new options of market approaches which would increase the complexity of modelling and result interpretation. We exclude a detailed analysis of the additional TV capabilities of GPON, only taking into account that IPTV is considered. Because there also exists Ethernet P2P equipment offering a RF colour on the same fibre used for the Ethernet signal with no significant additional cost, these RF-TV features will not cause any differences between the architectures we compare, hence this feature may be neglected without distorting results.

Providing 40 Mbps per customer on average could cause bottlenecks if many of these customers use high quality IPTV and Video on Demand (VoD) in parallel, e.g. during evening hours, if they use several receivers per home. Thus IPTV in a GPON environment often is implemented as dynamic multicast where only those TV-programs are broadcasted in an OLT string which are requested by the end users of that string. This may cause switch-over delays. This may happen in GPON architectures more often than in architectures with higher bandwidth per end customer, where more programs

31 RF – Radio Frequency.

may be broadcasted at the same time. Thus, we qualify the IPTV capability of GPON to be poorer than in the other architectures considered in this study.

2.3.3 GPON over a passive P2P plant

GPON can also be implemented on top of a Point-to-Point fibre architecture by "moving the splitters back" into the central MPoP location and having dedicated fibres in both drop and feeder section. Like in the first scenario the fibre count in the feeder and drop cable segment is the same, thus this GPON architecture does not have the fibre savings in the feeder segment as described before.

The reason why we consider this hybrid P2P/GPON architecture is the potential to combine advantages of both worlds. All fibres are terminated on the ODF and are accessible per patch cables. So every customer still has a dedicated fibre line to the MPoP, thus opening all future fibre and optical spectrum uses one may imagine and also allowing individual use of a single fibre as described in the previous P2P scenario. If not connected to the splitters and OLTs at the MPoP, but to other transmission systems, individual customers could be served with special products beyond the broadband mass market GPON products (e.g. 1 Gbps symmetrical traffic, 10 G or even optical frequency space based transmission). Beside this additional option individual customer demand may be served out of the GPON features as described before, whereby the reduction of the splitting ratio could be achieved in an easy manner at the central site just introducing new splitters without affecting the fibre plant in the field.

Locating the splitters at a central site allows a more efficient use of the splitters and the OLTs during the roll out of the services (ramp-up). This not only generates positive cash flow effects but also reduces some risk of investment. Only active subscribers would be patched from the main ODF via a network sided ODF port onto a splitter and from there to the OLT. This assures a very high degree of splitter and OLT efficiency (contrary to the standard GPON case with splitters in the field, OLTs will have a very high utilisation rate because only active subscribers are patched through).[32]

The use of longer access lines between splitters and end customers has no impact on the total optical budget of the GPON system since the feeder cable is shortened by the same length. Compared to cascaded splitters a larger splitter at a central site also means less fibre splits and therefore lower attenuation and potentially an improved optical budget due to less splitter attenuations.

There is also no change concerning the exchangeability and interoperability of GPON OLTs and ONU/ONT. But the flexibility of the Point-to-Point fibre plant allows one to exchange the transmission systems smoothly over time, one customer at a time, if that

32 At least in the beginning of a roll-out, GPON OLTs would suffer from low take-up while GPON over P2P OLTs could always be operated at their capacity limit.

looks favourable, and thus reduces the supplier dependency of the operator. This economic value per se[33] is neither quantified nor considered in our model assumptions.

Since the active equipment connecting to the customers still is GPON, the security and availability considerations for GPON described in the section above remain the same. But the underlying Point-to-Point fibre architecture allows individual services with improved features for dedicated customers in parallel without any additional fibre count. It would also allow a smooth migration to other architectures like Ethernet P2P, if that looks favourable at one point in the future or for a subset of customers.

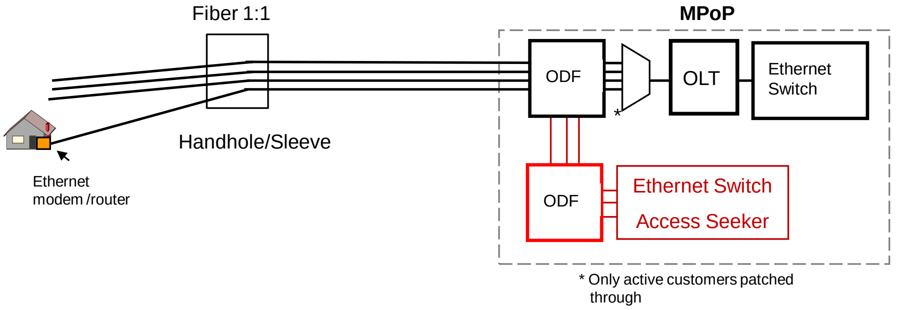
The space and the associated cost required at the MPoP sites will be higher than with GPON with distributed splitters (described in the previous section 2.3.2), because the ODF network and customer sided port counts are significantly higher (by the splitting factor) and the splitters themselves must be located at the MPoP sites, too. This will be considered in our bottom-up space demand model for the MPoPs. On the other hand, the distributed splitters and their associated cost in the field will be saved.

The demand of electrical power consumption during ramp-up will be lower in GPON with centralized splitters, since the OLTs will only be installed according to demand and subscriber increase. We will consider this also in our bottom-up MPoP OPEX modelling. The ramp-up effect however only will become visible in our dynamic modelling (section 3.1.8).

The associated wholesale product we have considered in this study is an unbundled fibre loop. From a wholesale perspective the scenario GPON over P2P unbundling is identical with the scenario P2P unbundling because it refers to the same P2P outside plant.

33 The ability to exchange suppliers without loss of service quality for the end user improves supplier competition and reduces equipment cost when new generations of systems have to be introduced. It also reduces migration cost and the risk of supplier insolvency etc.

Figure 2-8: Scenario GPON over P2P with fibre LLU



Incumbent cost (relevant for LLU price)
- •CPE
- •Access Network incl. inhouse cabling
- •ODF + Patch cabling + floorspace
- •Splitter + OLT + floorspace + Energy
- •Ethernet Switch + floorspace + Energy
- •Network sided Ethernet port (1 per MPoP)
- •Concentration Network
- •Core Network

Competitor Cost
- •CPE
- •LLU charge
- •Competitor's ODF & Patch cabling + floorspace
- •Ethernet Switch + floorspace + energy
- •Network sided Ethernet port (1 per MPoP)
- •Concentration Network
- •Core Network

Concerning outband RF-TV signal transmission there is no difference between the two GPON approaches. RF, however, is not considered in the modelling.

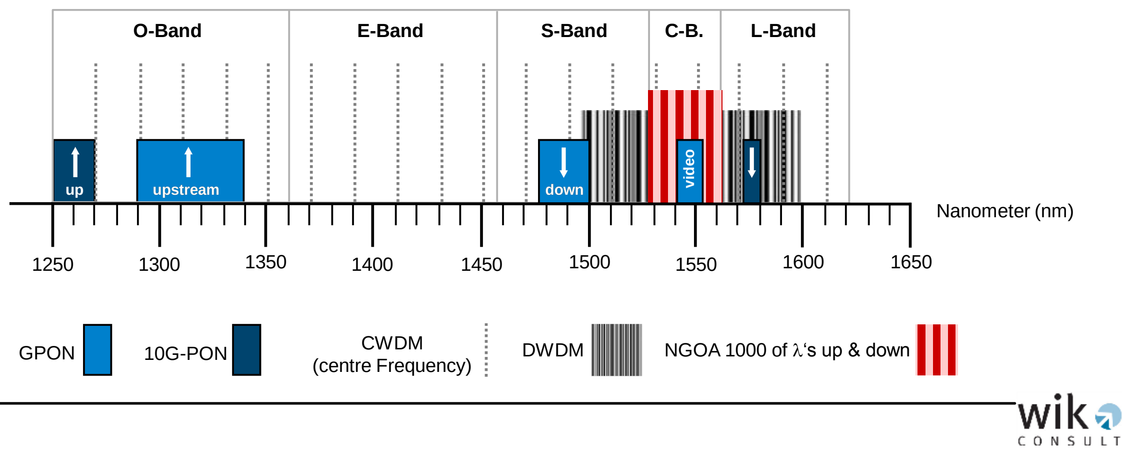
2.3.4 WDM PON

Using one optical fibre for several customers can be done in technologically different ways. GPON technologies use the same single optical beams and assign transmission rights to end users by a central administration (the OLT at the central site), so that each user can send his upstream information exclusively and without interference to other users in the same system in different time slots (TDM, Time Division Multiplex). WDM (Wave Division Multiplex) systems, however, use different optical beams of different wavelengths (different colours) to separate the transmitted information from each other. Hence, WDM is essentially a means of capacity expansion through reusing the physical medium optical fibre with more than just one wavelength.

GPON already multiplexes two (three when additionally considering analogue (RF) TV) wavelengths on the fibre. The Coarse WDM standard enables 18 separately distinguishable wavelengths and the Dense WDM standard enables 162 wavelengths with a much smaller channel width. GPON and C/DWDM as such cannot coexist on the same fibre (at least not without sacrificing some of the defined WDM wavelengths, see Figure 2-9). The more wavelengths are enabled, the smaller the spacing between two wavelengths becomes. Smaller channel width and spacing mean that lasers must be increasingly accurate. This is what has made the use of DWDM in the access network up to now so expensive.

System development proceeds and DWDM cost have significantly decreased over the last decade and will continue to decrease further on. Already today there are DWDM PON systems in the market that allow using up to 80 different colours of the DWDM grid in order to address customers individually[34] – or as customers grouped to an GPON overlay network. The WDM splitters allocate the individual colours to the appropriate fibre access lines connected to the splitters. Each colour is capable of transporting a 10 Gbps Ethernet signal. Tuneable transponders allow one to use "grey light" standard end customer equipment. In multi-dwelling buildings this large capacity may be shared in a FTTB manner by an Ethernet aggregation switch in the basement. At the central site the OLT routes the optical beams to different directions and thus allow one to unbundled single optical beams. Overall this DWDM based approach is not well suited to address the mass market already now, because it is oversized and still is rather expensive, so better suits for business customers and large multi-dwellings in a FTTB manner.

Figure 2-9: Use of the optical wavelength grid



Source: WIK/Schuster[35]

Recent research by Nokia Siemens Networks and other companies organized in the Open Lambda Initiative aims at enabling an enormous increase of wavelengths on the same fibre by facilitating technological progress in signal processing, tuneable lasers and photonic integration. This would allow high wavelength density and requires high receiver sensitivity, thereby enabling approximately one thousand individual wave-lengths in the C-Band of the spectrum alone (Next Generation Optical Access – NGOA), just affecting the GPON downstream channel bandwidth, being above and be-low the RF video wavelength of the GPON standard and above and below the 10G-

34 E.g. ADVA Systems, Munich, Germany.
35 Schuster (2010), modified by WIK.

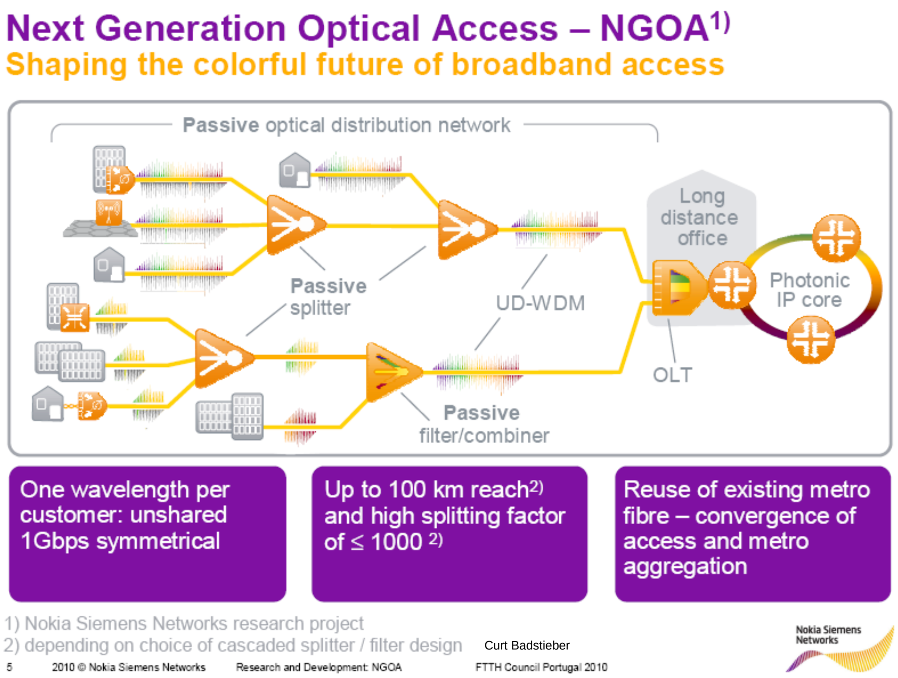
PON downstream channel wavelength). In this way, only coexistence between GPON and 10G GPON would be enabled. At the moment we see no option for coexistence between GPON and NGOA.

Such a WDM PON technology (Figure 2-10) would allow dedicated wavelengths for each customer, resulting in higher bandwidth compared to GPON. Each of these WDM PON wavelengths is announced to support 1 Gbps bandwidth, which can be administered by one or more WDM PON OLTs, operated by different carriers, thus allowing one to unbundle the wavelength.

To be precise, the aim of using WDM in this context is not to multiplex multiple GPON overlays on the same fibre but rather to enhance the capacity of the system by providing every customer with a separate wavelength of higher capacity which e.g. may be "unbundled", too.

So far, this is ongoing research and development, and it remains to be seen whether this technology can be commercialized. Suppliers forecast the market availability within approximately three years from now.

Figure 2-10: Outlook: WDM PON in future use



Source: Badstieber (2010)

Nevertheless we have considered a WDM PON technology such as the one proposed by the Open Lambda Initiative as a very forward looking technology option in this study.[36]

We assume that a single OLT supports up to 1000 wavelengths with 1 Gbps capacity each in a symmetric manner. The fibre plant may bridge a distance of up to 100 km. This allows one to close all of the existing MDF locations except those used for the core network, which consists of 45 locations in our model country Euroland (see section 3.1.2). The MDF will be replaced by larger manholes which host additional splitters (1:16) in order to further concentrate the fibres. Up to 1000 drop cable access lines would then be concentrated per backhaul fibre between the old MDF and the remaining MPoP at the core layer nodes. Up to the old MDF locations we assume the fibre plant to be the same compared to GPON (with splitters in the field), from there to the MPoP the existing concentration network will be replaced by backhaul fibres, hence by a passive optical network.[37]

Furthermore, we make advanced assumptions for the cost of the WDM PON equipment by assuming it will be produced in large numbers of components, thus costing more than GPON components. The OLT we assume to be 5 times more expensive than a GPON OLT, the ONT 1.5 times more expensive than a GPON ONT. The difference is caused by the higher complexity and bandwidth of the systems.[38] The central systems functionality of WDM PON at the MPoP is comparable to the GPON technology. The backhaul cables are terminated to an ODF, which allows one to patch the splitter chain to any OLT port. The OLTs are connected to high power Ethernet switches aggregating the traffic to the core routers. The space required in the MPoP and the electrical power consumption will be calculated bottom up like in all other calculations.

With this type of WDM PON architecture we have a dramatic increase of dedicated bandwidth per end customer (from 40 Mbps to 1 Gbps) but the bandwidth peak per customer is reduced to 1 Gbps compared to 2.5 Gbps in the shared GPON case. This solution only allows one to serve the end customers individually in the bandwidth frame the optical beam offers (1 Gbps). Higher bandwidth can only be offered by bundling colours. Dark fibre optical frequency bands for dedicated customers cannot be served and require additional fibres in the backhaul, feeder and drop segment. Supplier dependency and inflexibility for future system upgrade may remain the same since the system bases also on a Point-to-Multipoint fibre plant.

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36 Therefore our results may have some uncertainty.

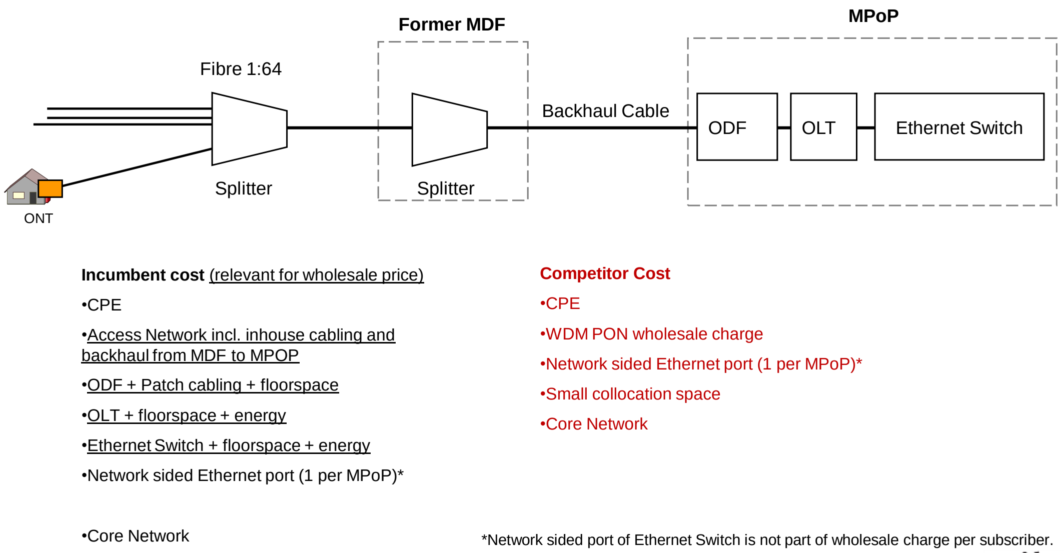
37 With 45 MPoPs the 22 million potential subscribers give on average 490,000 potential subscribers per MPoP. With a splitting ratio of 1:1000 only 490 fibres have to be concentrated at the MPoP, thus there is no question of fibre manageability. 45 circles with a radius of 50 km (100 km divided by 2 for fibre routing deviations) may certainly cover the whole Euroland. Therefore, we believe our assumptions to be reasonable.

38 The WDM PON OLT has 400 times more capacity (1000/2.5) than a GPON OLT and a much higher complexity of the optical systems, the WDM PON ONT has to deal with the much more complex wavelength grid at comparable speeds. For the WDM PON ONT price we also conducted sensitivities.

We assume that the disadvantages of the GPON security and availability constraints will not exist in the WDM PON architecture, which does not use broadcast for individual communication and only transmits the end user information over the end users access line.

Accordingly, the associated wholesale access considered is an active line access at the core level, which we call "WDM PON unbundling". The underlined cost components in Figure 2-11 once again are the input for the wholesale price calculation, while the components in black build the total cost of the incumbent and those in red the total cost of the competitor.

Figure 2-11: Scenario WDM PON with unbundling at the core level



To our knowledge the WDM PON solutions do not implement the RF-TV approaches of GPON and Ethernet P2P, but in principle we see no technical hurdles to add an additional optical beam for this purpose, if there is demand for it. Thus we see no competitive differences between the architectures considered concerning RF-TV and believe the exclusion of this option to be justified.

2.3.5 Comparison of technologies considered

The following table provides a comparison of all solutions considered. Generally Point-to-Point outside plants (deployed in the case of P2P and GPON over P2P) are better suited for higher and symmetrical bandwidth and therefore also better able to cater to business users. P2P outside plants are more future proof because they can be flexibly upgraded according to the demand of future customers. In addition, P2P allows the operator to source from multiple equipment vendors much more easily than all PON variants. PON variants (GPON over P2P, GPON and WDM PON) on the other hand require fewer fibres in the feeder segment and save on MPoP footprint and potentially on energy consumption. Our cost modelling analysis will specifically address the latter aspects to analyze the cost advantages in this respect. Most of the other qualitative differentiating factors (performance, ability for unbundling, scalability, fault identification, security, etc.) are not part of the quantitative analysis.

Table 2-3: Comparison of access solutions considered

	P2P	GPON over P2P	GPON	WDM PON
Fibre count drop / feeder	◑ / ○	◑ / ○	◑ / ●	◑ / ●
Bandwidth per customer / capability for symmetry	● / ●	◑ / ◑	◔ / ◑	◕ / ●
Max distance from MPoP to customer	10-40km	20km	20km	100km
Ability to cater to business customers	●	◕	◔	◑
Future-proof	●	●	◑	◑
Security	●	◑	◑	◕
Degree of vendor-independency	●	◔	◔	◔
Energy consumption MPoP	○	◕	◑	●
Fault identification and repair	●	◑	◔	◔
Floorspace demand at MPoP	○	◑	◕	●

Relatively good ● **Relatively poor** ○

Source: WIK-Consult

2.4 Competitive models not considered

There are two models or scenario variants which are close to the scenarios considered, for which we have decided not to analyse in the competition model.

The first variant would be in the wholesale entrant sphere, an entrant using **bitstream** instead of unbundling fibre loops of the existing **Point-to-Point** fibre plant of the P2P and GPON over P2P architectures. This variant would not add significant findings, and would not contribute to the discussion of architectural differences, since the bitstream has most of the quality disadvantages a bitstream access product produced by GPON also has. Both strongly depend on the wholesale providers performance and service quality.

The second variant will show an **entrant who replicates the incumbent's NGA** infrastructure to the end customers' homes. As we will show in chapter 3 infrastructure replicability is only (theoretically) viable in Cluster 1 of Euroland, we do not believe this approach to have major relevance, but including it would bring major complexity into the competitive model. The coverage of the other scenarios at least reaches Cluster 4 and the cost curve would differ compared to the other entrants. Therefore we have excluded this variant.

In addition to these 2 variants there is another case we have neither modelled in the steady state model and its dynamic extension nor in the competition model: This is the case of **sub-loop unbundling** at the DP in order to obtain access to unbundled fibre lines in the Point-to-Point drop fibre plants. These architectures require a competitor's infrastructure not only to the MPoP, but in addition to the DPs in the field. So the feeder fibre lines have to be replicated by the competitors. This reduces profitability compared to all scenarios considered (ULL and bitstream) and is the reason why we did not include this case into our considerations.

2.5 Critical market shares for competitive models

The cost model determines which take-up rate an operator needs to realise in order to bring his total cost below revenues per user. These critical market shares (see section 3.2.1) also formed the basis of determining the number of firms in the initial competitive model design. Since critical market shares of competitors have shown to be relatively high except in the first two clusters it became apparent that the number of firms in the competitive model would very likely be in the single-digit range. Later calibration of the model then confirmed this expectation. As a result, we are looking at about 4-6 firms competing in the free entry equilibrium.

In the cost model the ARPU is fixed and market shares are only referenced to in order to compare ARPU with cost. In the competitive model however, price is a function of competition and so is the effective market share in the equilibrium.

2.6 Competitive and regulatory interaction in an oligopoly environment

2.6.1 Modelling approach

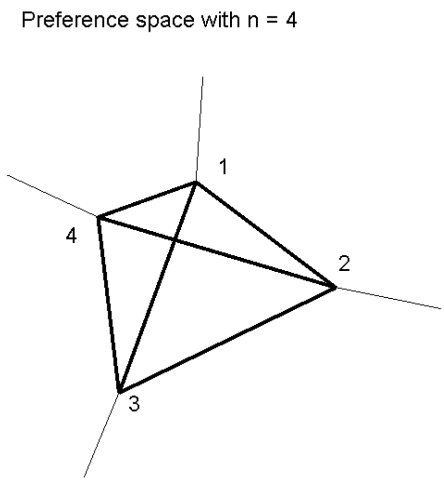
2.6.1.1 The theoretical model

Our modelling approach is based on the pyramid model, which is closely related to the spokes model:[39] For each pair of services, there is a set of consumers who choose between these two products and these consumers are (uniformly) distributed in their

39 The pyramid model was first developed by von Ungern-Sternberg (1991), while the spokes model originates from Chen and Riordan (2007).

willingness to pay for one service rather than the other. Graphically this leads to a pyramid, as illustrated in Figure 2-12, with each service located at one of the tips of the pyramid. In addition, there may be "Hinterland" consumers who consider only one of the services, represented as the thin lines emanating from the tips.

Figure 2-12: Preference space



An alternative would be the Salop model, which is widely used in the industrial organization literature.[40] A major disadvantage of the Salop model is that it imposes a very particular substitution pattern across products: A service is a substitute only to its two neighboring services implying that cross price elasticities to other services are equal to zero. Our modelling approach allows for positive cross price elasticities between any pair of services.

Another frequently used model is the logit model.[41] Our approach and the logit model have in common that all cross price elasticities are strictly positive. While our approach is in general very flexible, our chosen implementation and the logit model have in common that a given number of available services are affected symmetrically by the introduction of an additional service. In terms of implementation, an advantage of the present framework leads to linear demand functions and, thus, explicit solutions. This is not the case for the logit model.

Infrastructure. Our approach captures essential aspects of competition in FTTH markets, both on the wholesale and retail side. One firm, the "incumbent", owns and invests in an FTTH access network, to which other firms ("entrants") must obtain access in or-

40 See Salop (1979).
41 For an extensive treatment, see Anderson, de Palma and Thisse (1992).

der to provide NGA-based services. Entrants are assumed to be symmetric and need to make own investments in order to use NGA access. We consider models both with and without a second vertically integrated broadband infrastructure (“cable”), to which no other firms have access.

Demand. The services that firms offer are both “horizontally” and “vertically” differentiated. The former means that consumers do not react strongly to small price differences because individual preferences for firms’ brands differ. In particular, assuming a uniform distribution of individual tastes in this horizontal dimension leads to linear demand functions. As a result of horizontal differentiation, the market is imperfectly competitive and firms will enjoy positive mark-ups. Vertical differentiation expresses differences in service quality and goodwill or brand recognition as perceived by consumers, i.e., at equal prices a firm with higher service quality would attract more consumers. Service quality is assumed to affect all consumers similarly, i.e. we abstract from market segmentation in the service quality dimension.

To model that total FTTH subscription demand is variable, we consider two model variants. In both there is a group of “competitive” subscribers. Each competitive subscriber makes a first choice between two of the firms, and unless their offers are very unfavorable, he will choose one of the two. It is assumed that all pairs of preferred firms (before quality differences) are equally likely in the population, so that effectively each firm will compete with any other firm for consumers. Formally speaking, cross price elasticities are different from zero for all product pairs. Due to the assumption of uniform distributions of consumer tastes, the resulting demand function of each firm is linear in its own price and linear in the price of all other firms. This makes the analysis tractable and allows for explicit solutions. In spite of advances in empirical demand estimation that allow for more flexible demand specifications, the linear demand system remains popular in empirical research. Our underlying micro foundation permits us to compare markets with different numbers of firms in a meaningful way.

If the firms on the market include the cable firm, our model has the feature that FTTH subscription demand is variable. However, total demand for subscription is fixed and assumed to be 100% of potential subscribers in the clusters considered. For reasons that become clear in a moment, we call this the “No-Hinterland” model. In the absence of a non-FTTH-based competitor, we make subscription demand variable with the introduction of “captive” consumers who make a choice between one firm and not buying FTTH subscriptions at all (this is the “Hinterland” model). Here we aim at FTTH subscriptions close to 70% of all potential subscribers in the clusters considered.

All subscribers then either buy one subscription or none, where competitive subscribers will always buy one subscription. Not buying leads to a surplus normalized to zero, while the choice between the two preferred options is based on the comparison between prices, quality of service and the relative preference for the two brands.

Cost structure. We consider market outcomes on a monthly basis, so investment cost for providing or using NGA have been translated into a monthly value over the life time of the infrastructure. Each firm also bears downstream costs which consist of a fixed part and a variable part as a function of number of subscribers. For the latter, the model allows for either increasing or decreasing marginal cost. In the actual model runs we have only used constant marginal costs, though.

The access tariff paid by the entrants to the incumbent consists of a price per subscription and potentially also of a fixed fee. In this study we are considering only linear wholesale access tariffs based on the incumbent's LRIC at a defined network load. In one variant of the model, we determine the linear access tariff such that at the resulting equilibrium quantity, the access payments exactly cover the total cost of providing FTTH access (interpreted as LRIC pricing).

We treat the incumbent as if he were under vertical accounting separation into a NetCo that supplies FTTH infrastructure access and an OpCo that sells FTTH end-user services. The incumbent's NetCo sells access to other firms ("entrants") and to the OpCo. This does not affect pricing behavior and overall profits but it provides for an automatic price-squeeze test.[42]

All cost components consist of fixed costs and constant variable costs, but we could also include a quadratic term to model non-constant variable cost.

Incumbent:

- Costs of wholesale products for the whole FTTH output
- Opportunity costs of wholesale products for own end-user sales
- Downstream network (concentration and core network) and retail costs for own end-user sales.

Competitors/entrants:

- Price of wholesale products purchased
- Downstream network (concentration and core network) and retail costs for end-user sales.
    - Entrants/competitors are modelled on a scorched node basis, where nodes are determined by the incumbent‘s network architecture.
    - Entrants fully penetrate each modelled cluster.

42 In our model runs price squeeze has never been an issue.

Cable TV/DOCSIS3

- Total costs of own end-user sales

The price of wholesale products is assumed to be based on the long-run incremental costs (LRIC) of the access service, which in turn contain the fixed and variable costs incurred by the incumbent for the FTTH access product. Here the variable costs include wholesale sale costs. These wholesale sale costs are saved when the incumbent provides the access product internally to himself. A linear wholesale charge is then the total LRIC divided by the FTTH access quantity (including access used internally by the incumbent). On top of this, there may be a multiplicative mark-up on the pure LRIC to arrive at the wholesale charge.

Equilibrium. Depending on the scenario considered, first, firms make certain investments in networks and access, which determine their service quality levels and operating cost. Second, they compete in subscription fees at the retail level. The resulting market outcome is modelled as the Nash equilibrium outcome of the resulting pricing game, from which subscriber numbers, profits, market shares, consumer surplus and total welfare are derived.[43] In the model with entry and exit, we first allow for a non-specified process of entry and exit with the feature that all active entrants make profits and that the entry of an additional entrant would lead to losses of all active entrants. Here we postulate that entrants correctly foresee the effect of entry (and the associated investment decisions) on the pricing decisions and, thus, on market outcome. Formally, and in line with the literature on industrial organization, the stronger notion of subgame perfect Nash equilibrium is used. This means that we consider subgame perfect Nash equilibria of the two-stage game in which entrants first make their participation decision and then all active firms make pricing decisions.

2.6.1.2 The quantitative model

More detailed and formal descriptions of the competitive model are provided in Annex 4. In the market for broadband, n firms (the incumbent, entrants and potentially a cable company) compete for N_c “competitive” consumers and possibly N_e “Hinterland” consumers. Each firm provides a quality level S_i. The intensity of preferences of consumers between services supplied by firms i and j are measured by σ_{ij}, and λ_i is the intensity of preferences in the Hinterland of firm i.

After investments have been made, firms compete in subscription prices. Market outcomes are given by the Nash equilibrium of this pricing game between firms.

Providing FTTH access involves a marginal cost of c_0 and a fixed cost of K_0. Firm i’s downstream costs of providing retail services consist of a marginal cost c_i and a fixed

43 The Nash equilibrium is the standard solution concept used in the literature. It assures that firm decisions are mutually consistent.

cost K_i. Downstream firms pay an access tariff consisting of a per-subscriber price a and (potentially) a fixed fee A. Only the incumbent receives wholesale payments ($\gamma_1 = 1$ and $\gamma_i = 0$ for the other firms), but all firms apart from the cable company use the incumbent's FTTH access ($\delta_i = 0$ for cable, and $\delta_i = 1$ for all other firms)

Model output variables. The following variables are determined at the equilibrium outcome:

- p = final output subscription price
- n = the equilibrium number of firms. While the number of firms is actually an input into the quantitative model, we determine the free-entry equilibrium number by running the model with an increasing number of entrants, until under n firms entrants are profitable while under (n+1) firms entrants expect to make losses.
- prof = profits per month per firm
- WhProf = wholesale profits of incumbent. These include profits from the sale of the incumbent's Netco to the incumbent's Opco.
- s = market share per firm
- sum(q) = market output
- CS = consumer surplus per month. It has to be noted that total output (including cable) does not vary in the No-Hinterland model, whereas in the Hinterland model it does not vary for competitive subscribers but does vary for Hinterland subscribers.
- W = welfare per month = CS + sum(prof). Aside from market expansion effects in the Hinterland markets the main welfare effects stem from cost and WtP differences of the various technologies and suppliers. Among others, welfare is affected by changes in the market shares of the different technologies and by changes in the market shares of the different providers using the same technology. With endogenous entry, also the duplication of fixed costs affects the welfare analysis.

2.6.1.3 QoS and willingness to pay in the basic model

Our assumptions on quality of service (QoS) and the end-users' willingness-to-pay (WtP) are provided in Table 2-4. The values are in Euro-equivalent per month.

Table 2-4: QoS and WtP assumptions for basic model

QoS, Scenario	Incumbent QoS =WtP	Cable QoS = WtP	Entrant QoS	Entrant WtP
P2P unbundling	100	82	99	97
GPON over P2P unbundling	99	82	99	97
WDM PON unbun-dling	95	82	91	89
GPON bitstream core	90	82	85	83
GPON bitstream MPoP	90	82	87.5	85.5

The value of chosen QoS differences may appear large from today's perspective. However, it has to be kept in mind that we are considering steady state situations with full FTTH penetration around ten years from now. It can be expected that the share of customers with high-bandwidth demands and the prevalence of corresponding applications will be much higher than now. Thus, the premium for ultra-high bandwidth will also be much higher than now.

In contrast, the incumbency premium will likely become smaller, as time goes by. This justifies the small incumbency premium of 2 € over entrants that we have chosen.

Quality differences between architectures refer to incumbents, entrants and cable and are explained as follows.

Incumbent:

- **1) P2P Ethernet:** This is the base case with best quality (QoS = 100). Each customer can be served with individual bandwidth up to 10 Gbps according to demand.
- **2) GPON over P2P:** In this case users share down- and upstream capacity and influence each other. However, the operator can scale the degree of sharing very flexibly by controlling split factors. Compared to P2P Ethernet this is poorer for IPTV and more sensitive to security and availability for end-users. Due to P2P fibres individual services for dedicated customers up to 10 Gbps or in the optical spectrum in separate technology are possible (-> QoS = 99).
- **3) WDM PON:** In this case users share down- and upstream lines on a per color base, resulting in about 1 Gbps per customer. Compared to P2P Ethernet this is poorer for IPTV and is sensitive to security. The shared fibre is inflexible for dramatic bandwidth upgrades so that there can be no 10 Gbps lines or WDM use (-> QoS = 95).

- **4) GPON:** In this case users share down- and upstream capacity and influence each other. Any bandwidth guarantee per customer is limited (< 40 Mbit/s) or dependent on statistical behavior. Compared to P2P Ethernet this is poorer for IPTV and is sensitive to security. The shared fibre is inflexible for dramatic bandwidth upgrades (-> QoS = 90).

Entrant:

- **1) Unbundling of P2P Ethernet:** This is the base case with best quality for entrants enabling ULL for entrants, but because the value chain is partially predetermined by the incumbent and because entrants depend on the incumbent for service and repairs, slightly poorer quality may result. Each customer can be served with individual bandwidth up to 10 Gbps according to demand (-> QoS = 99).[44]

- **2) Unbundling of GPON over P2P:** This case allows ULL for entrants with advantages as above (-> QoS = 99).

- **3) Unbundling of WDM PON:** In this case the value chain is strongly dependent on the incumbent, but the bandwidth guarantee is rather high (~1 Gbit/s per customer). The service is sensitive to security. The shared fibre is inflexible for dramatic bandwidth upgrades. So, there can be no 10 Gbps lines, dark fibre or WDM use (-> QoS = 91).

- **4) Bitstream access of GPON:** Value chain in this case is strongly dependant on the incumbent. Any bandwidth guarantee per customer is limited (< 40 Mbps) or dependent on statistical behavior. The handover at core locations is poorer than at MPoPs (bitstream core -> QoS = 85, bitstream MPoP -> QoS = 87.5).

Cable:

- Cable is a shared technology that is inferior to FTTH in all the above versions and compared to incumbents and entrants.

Scope of results

- We have done model runs based on the final cost model outputs.

- This resulted in runs for all scenarios for the aggregate of Clusters 1 through 4. We have done this for both the Hinterland model and the No-Hinterland model. This way we can generate comparable results for all scenarios and for both models. In addition we have done selective model runs for GPON bitstream core

44 Nevertheless, we assume that wholesale services are provided under non-discriminatory conditions. This means under a perfect regulatory regime. Imperfect regulation would imply larger quality differences between incumbent and entrants, See Footnote 52 below for incentives of the incumbent to deteriorate quality of wholesale access.

for Clusters 1 through 5, because the critical market share analysis[45] indicated that competitive entry in Cluster 5 was feasible for the GPON bitstream core scenario.

- The remaining discretionary data inputs (horizontal differentiation and size of Hinterland) were calibrated to be compatible with the assumed ARPUs, with plausible quality differences and with plausible market shares. We have kept these parameters constant across scenarios and only adapted them to different market sizes. Reduced product differentiation would have led to fiercer competition, resulting in a smaller equilibrium number of firms.

2.6.2 Basic model results

In this section we provide results on prices, profits, market shares, consumer surplus and welfare for all scenarios over the first four clusters. These basic model runs have all been performed under strong regulation and do not differentiate between weak and strong regulation. Weak regulation with mark-ups on wholesale access prices is taken up in section 2.6.2.5. Section 2.6.2.6 endogenizes the access charges based on actual equilibrium access quantities. Section 2.6.2.7 considers the marginal Cluster 4 in isolation, in order to find out if investment in that cluster is profitable for the incumbent and/or entrants under the basic model assumptions. Last, we include Cluster 5 for the GPON bitstream core scenario in section 2.6.2.8.

The cost data and wholesale charges for the different scenarios are generally taken from the results of the cost model. Except when noted differently the costs and wholesale charges are generally the aggregate numbers for the first four clusters. The cost data for cable were assumed by us to reflect reasonable estimates.

2.6.2.1 Results on end-user prices

There are three drivers of prices and price differences: Costs, WtP and competition (number of firms). In addition to the WtP shown above in Table 2-4 we, therefore, have to consider the relevant costs. Prices are directly driven by variable or, more precisely, marginal costs (MC), not by fixed costs. Fixed costs only influence the level of profits and are, thus, important for entry and exit of firms (which again indirectly affect prices).[46]

In Table 2-5 below MC_C and MC_E are the actual marginal costs incurred by cable and entrants and are directly relevant for their retail pricing; the values for MC_C have been assigned by us and the values of MC_E have been determined from cost model results. For the incumbent, MC_{I_actual} are the sum of MC of access and downstream services,

45 The concept of critical market shares is developed in section 3.2.
46 The aggregate fixed costs of cable for the first four clusters are assumed to be 20 Mio € per month.

while $MC_{I\_perceived}$ are the sum of wholesale access charges and downstream costs. In contrast to MC_{I_actual} the $MC_{I\_perceived}$ are directly relevant for the incumbent's end-user pricing because selling wholesale rather than retail is the next best use of the incumbent's FTTH infrastructure. Prices above $MC_{I\ perceived}$ also fulfill the condition of being margin squeeze free. The marginal cost of the entrants MC_E are the sum of the wholesale access charges and the (variable) downstream costs.

Table 2-5: Marginal costs in Euro per month

Scenario	MC_C	$MC_{I\ actual}$	$MC_{I\ perceived}$	MC_E
P2P unbundling	12.00	20.18	34.36	36.22
GPON over P2P unbundling	12.00	18.05	32.22	36.22
WDM PON unbundling	12.00	18.36	33.37	34.00
GPON bitstream core	12.00	16.46	31.99	32.62
GPON bitstream MPoP	12.00	16.46	31.53	32.16

Source: WIK estimates

The equilibrium end-user prices for all scenarios are shown in Table 2-6. While the first two scenarios consistently lead to the highest prices, the order of prices overall differs between the Hinterland and the No-Hinterland model. Because of product differentiation the incumbent's price may be below the entrants' price (for instance, in case of GPON over P2P unbundling) if the incumbent's variable costs are sufficiently lower to offset for quality and goodwill differences which tends to lead to a higher price. In the No-Hinterland model the equilibrium number of firms is in two cases (P2P unbundling and GPON bitstream MPoP) one higher than in the Hinterland model. In both these cases the order of prices between Hinterland and No-Hinterland model is affected by this difference. Figure 2-13 and Figure 2-14 below illustrate the effect of the number of firms, 'n', on prices.

Table 2-6: Marginal costs and prices in Euro per month

			Hinterland			No-Hinterland			
Scenario	$MC_{Iperceived}$	MC_E	n-1	p_I	p_E	n-2	p_I	p_E	p_C
P2P unbundling	34.36	36.22	3	46.32	44.87	4	42.07	42.37	23.76
GPON over P2P unbundling	32.22	36.22	3	44.71	44.72	3	43.58	45.54	27.92
WDM PON unbundling	33.37	34.00	4	42.46	38.69	4	41.24	39.32	26.16
GPON bitstream core	31.99	32.62	4	41.58	37.44	4	40.10	37.63	28.28
GPON bitstream MPoP	31.53	32.16	3	43.04	40.52	4	38.76	37.67	27.15

Figure 2-13: Prices and number of firms Scenario GPON bitstream core, Hinterland

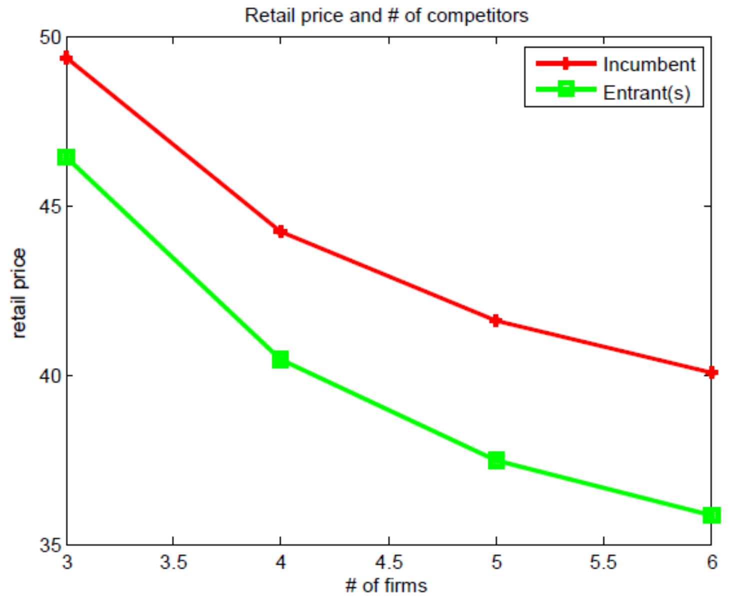
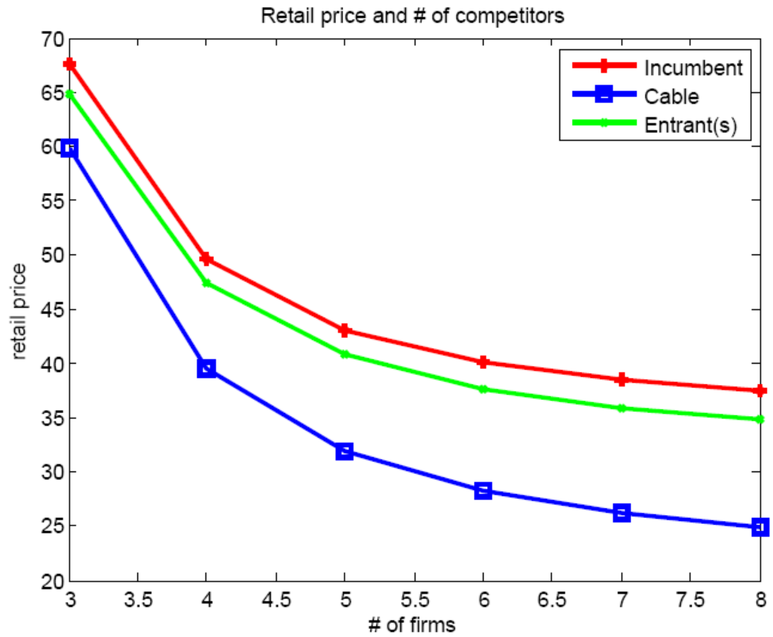


Figure 2-14: Prices and number of firms Scenario GPON bitstream core, No-Hinterland



The above illustrations in Figure 2-13 and Figure 2-14 for GPON bitstream core are derived by running the model with varying numbers of firms while keeping all other input variables of the model constant (and thus treat entry and exit as exogenous). The results are representative for all scenarios. The curves are always downward-sloping and convex. Retail prices are thus quite sensitive to the number of firms in the market, if the number of firms is small. Note that under the basic parameterization in all scenarios only 3 or 4 entrants survive in equilibrium.

The absolute price differences between incumbent and entrants increase slightly and the relative differences increase significantly in the number of firms. This suggests that entry increases competition among entrants by more than competition between the incumbent and entrants. Competition by cable brings prices of entrants and the incumbent much closer together than competition without cable.

Since the Hinterland model has one less firm than the No-Hinterland model, a direct comparison between both models would be for 3-7 firms in the Hinterland model and for 4-8 firms in the No-Hinterland model. In these ranges the two models yield quite similar results.

Table 2-7 shows the case of 5 firms in the Hinterland model and 6 firms in the No-Hinterland model, leading to 4 entrants in each case. Both models give the same rankings of the scenarios for prices of incumbents and entrants. However, on average prices are a little higher in the Hinterland model than in the No-Hinterland model. Prices of incumbents are always higher while prices of entrants are always lower in the Hinterland model than in the No-Hinterland model.

Table 2-7: Prices in Euro per month in case of 4 entrants for all scenarios

	Hinterland				No-Hinterland					
Scenario	p_I	**Rank**	p_E	Rank	p_I	**Rank**	p_E	Rank	p_C	Rank
P2P unbundling	43.78	1	41.64	1	42.07	1	42.37	1	23.76	5
GPON over P2P unbundling	41.78	3.5	41.51	2	40.38	3.5	42.17	2	24.11	4
WDM PON unbundling	42.46	2	38.69	3	41.24	2	39.32	3	26.16	3
GPON bitstream core	41.58	3.5	37.44	4.5	40.10	3.5	37.63	4.5	28.28	1
GPON bitstream MPoP	40.29	5	37.42	4.5	38.76	5	37.67	4.5	27.15	2

Table 2-7 clearly shows that the ranking of scenarios by the end-user price of cable differs substantially from the rankings of scenarios by the end-user prices of the incumbent and entrants. This holds because cable has in all scenarios distinctly lower marginal costs than the incumbent and entrants, while the difference in customer valuations between cable and the incumbent's and entrants' services varies substantially by scenarios. End-user prices for cable therefore vary inversely to the relative difference in WtP between cable and FTTH services.

The rankings of the scenarios in terms of the incumbent's and entrants' end-user prices are not all the same except for P2P unbundling which has always the highest and GPON bitstream MPoP which has always the lowest prices. GPON over P2P unbundling and WDM PON unbundling are very close to each other below P2P unbundling, and GPON bitstream core is somewhat above GPON bitstream MPoP.

If one therefore keeps the number of firms constant the equilibrium results would show P2P unbundling to have the highest prices followed by GPON over P2P unbundling and WDM PON unbundling. GPON bitstream core would be next and GPON bitstream MPoP last. The price rankings follow quite closely those of marginal costs, and any deviations are explained by higher or lower customer valuations of the services.

2.6.2.2 Results on profits

Table 2-8 gives profits for the basic model for both the Hinterland and the No-Hinterland case. It should be noted that entrants' profits are always reported per entrant.

Table 2-8: Profits in Million Euro (per month)

	Hinterland			No-Hinterland			
Scenario	n-1	$prof_I$	$prof_E$	n-2	$prof_I$	$prof_E$	$prof_C$
P2P unbundling	3	24.83	3.74	4	18.78	0.45	2.81
GPON over P2P unbundling	3	27.89	3.38	3	26.91	6.55*)	13.22
WDM PON unbundling	4	13.05	1.83	4	17.91	2.92	13.09
GPON bitstream core	4	23.71	1.54	4	13.22	2.07	23.72
GPON bitstream MPoP	3	23.60	4.40*)	4	10.00	0.31	17.86

*) with 4 entrants there is a very small loss for each entrant.

Because of the additional competition of cable in the Hinterland model, profits are not directly comparable between the Hinterland model and the No-Hinterland model.

In the Hinterland model entrants' profits are substantially higher in the three-entrant markets (P2P unbundling, GPON over P2P unbundling and GPON bitstream MPoP) than in the four-entrant markets (GPON bitstream core and WDM PON unbundling). Only in the WDM PON unbundling scenario seem the profits of the incumbent to be impacted by the number of competitors in the Hinterland model. As Figure 2-15 and Figure 2-16 show, this is mostly driven by additional competition.

In the No-Hinterland markets entrants' profits are much lower in those markets, whereas the Hinterland model has one less entrant in equilibrium. The reason is that there is a knife-edge entry of one more firm in the No-Hinterland model in those scenarios (P2P unbundling and GPON bitstream MPoP). Had fixed costs been just a little higher there would not have occurred this extra entry.

As has been the case with end-user prices, profits of cable services follow largely the quality differentials to FTTH in the various scenarios. The greater the differential the lower is cable's profits.

As Figure 2-15 and Figure 2-13 show, the influence of the number of entrants on profits differs somewhat from the entry effect on prices. The reason lies in wholesale profits. In the Hinterland model wholesale profits (because of the associated increase in overall output) increase in the number of firms, thereby increasing the difference between entrants' profits per firm and the incumbent's overall profits. In the No-Hinterland case the incumbent's wholesale profits are, because of the intervening effect of cable output, first increasing and then decreasing in the number of firms, resulting in a closing of the gap between entrants' profits per firm and the incumbent's overall profits.

Figure 2-15: Profits and number of competitors – GPON bitstream core, Hinterland

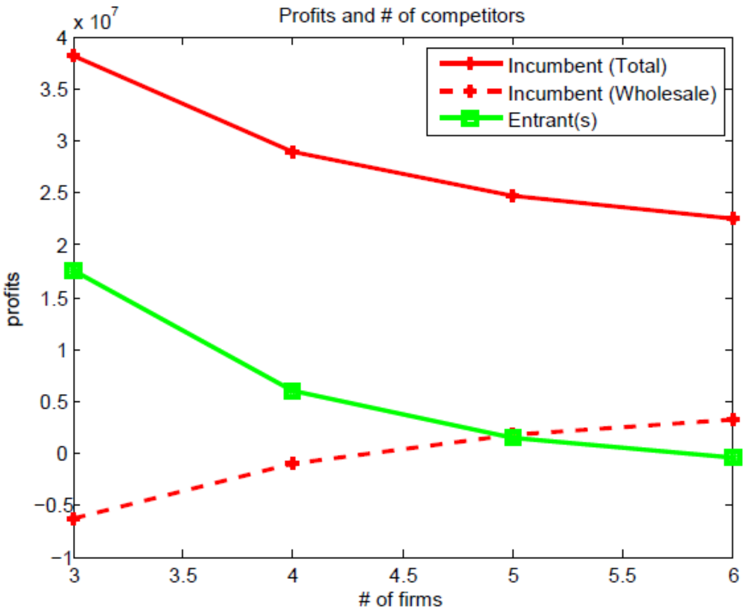
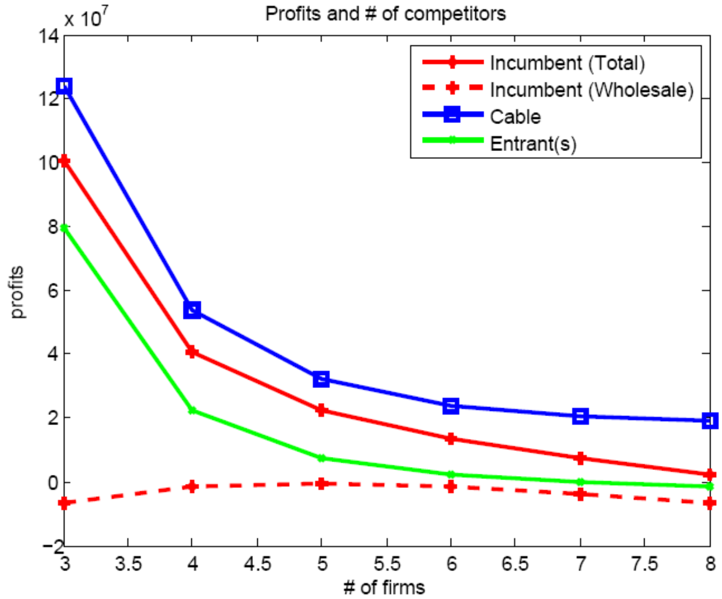


Figure 2-16: Profits and number of competitors - GPON bitstream core, No-Hinterland



Because of the increase in FTTH market output[47] that is associated with entry the wholesale profits increase with entry, although at a decreasing rate.

Otherwise, all firms experience a decline in profits per firm, as the number of firms increases. However, this happens at a declining rate, suggesting in particular that profits per entrant do not change dramatically around the free-entry equilibrium if the number of firms is fairly large. However, in the range of our equilibria (4-5 firms in the Hinterland model and 5-6 firms in the No-Hinterland model) profits do change substantially with entry.

2.6.2.3 Results on market shares and number of firms

Table 2-9 provides market shares in the basic model. It should be noted that entrants' market shares are always per entrant.

47 We are referring here to a relative shift of market shares between cable and the FTTH network.

Table 2-9: Market shares ‘s’ in percent

	Hinterland			No-Hinterland			
Scenario	n-1	s_I	s_E	n-2	s_I	s_E	s_C
P2P unbundling	3	40.7	19.8	4	23.4	13.5	22.5
GPON over P2P unbundling	3	42.1	19.3	3	26.3	16.5	24.2
WDM PON unbundling	4	41.4	14.7	4	24.5	12.1	27.1
GPON bitstream core	4	43.4	14.1	4	24.8	11.0	31.1
GPON bitstream MPoP	3	41.5	19.5	4	22.6	12.1	28.9

Even if one fully corrects for the presence of cable the incumbent’s market share in the No-Hinterland model is consistently smaller than in the Hinterland model.

In both models the incumbent’s market share stays in a narrow range through all scenarios, although it varies more in the No-Hinterland model than in the Hinterland model.

In the No-Hinterland model the market share of cable varies substantially. It closely follows quality differences between cable and FTTH and is lowest where the quality differential to FTTH is greatest.

As Figure 2-17 and Figure 2-18 show, the market shares sometimes react in a non-monotonic fashion to market entry. It is, in particular, noteworthy that, in the Hinterland case, the market share of the incumbent *increases* at some point as entry increases further. This appears to be restricted to the GPON bitstream core scenario, while in other scenarios the incumbent’s market share only tapers off as more firms enter.

Figure 2-17: Market shares and number of competitors – GPON bitstream core, Hinterland

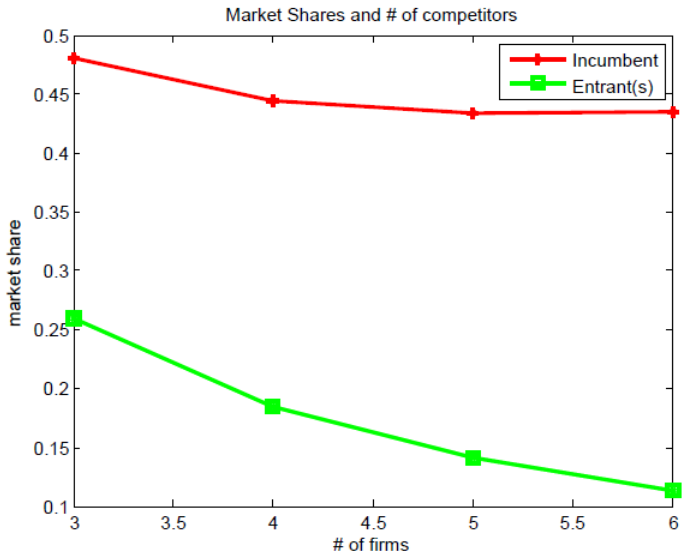
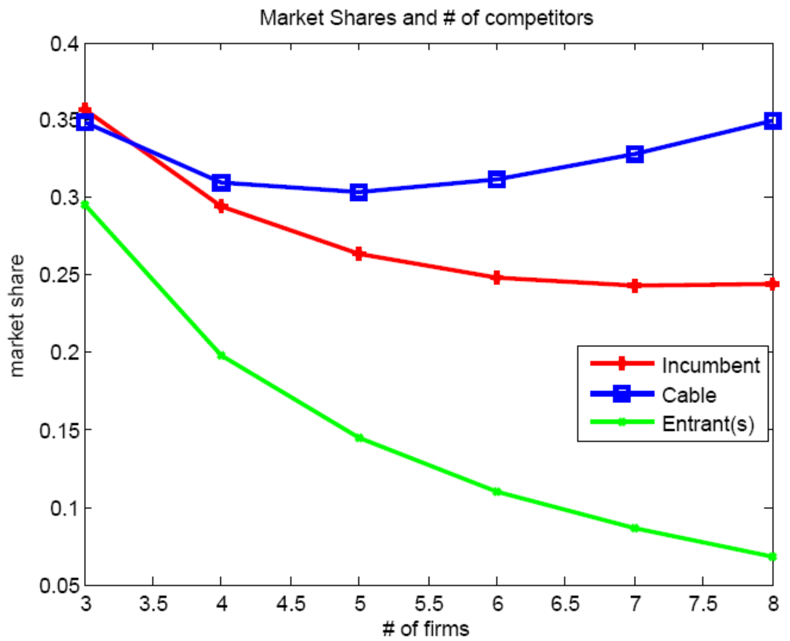


Figure 2-18: Market shares and number of competitors - GPON bitstream core, No-Hinterland



In the No-Hinterland case cable experiences at some point a market share increase as the number of entrants increases further.

Under the basic parameterization in all scenarios only 3 or 4 entrants survive in equilibrium. While we had expected this for all the other scenarios, it has come as a surprise for GPON bitstream core, where our expectation based on the critical market shares was for a higher number of entrants. The main reason is that, already with a small number of entrants, the low WtP for GPON leads to prices below the general ARPU assumed for the critical market share analysis. Further entry then leads to even lower prices and lower quantities per entrant, resulting in overall losses for all entrants.

2.6.2.4 Results on consumer surplus (CS) and welfare (W)

Table 2-10 summarizes our basic model results for CS and W. It also puts the results on prices, profits and market shares in perspective. In this context it needs to be noted that CS is largely driven by the price/valuation relationships between the different technologies and firms rather than by the overall quantity of output, which is fixed in the No-Hinterland model and varies only for each firm's backyard in the Hinterland model.

Table 2-10: Basic model results on consumer surplus and welfare per month

Scenario	Hinterland					No-Hinterland				
	n-1	CS		W		n-2	CS		W	
		Mio €	Rank	Mio €	Rank		Mio €	Rank	Mio €	Rank
P2P unbundling	3	243.1	2	279.2	2	4	466.9	1	490.3	2
GPON over P2P unbundling	3	245.6	1	283.6	1	3	434.0	2	493.8	1
WDM PON unbundling	4	240.5	3	270.8	3	4	431.2	3	473.9	3
GPON bitstream core	4	216.8	4	247.7	4.5	4	400.5	5	445.7	4.5
GPON bitstream MPoP	3	208.6	5	245.4	4.5	4	416.0	4	445.1	4.5

The ranking of CS in the Hinterland model is very close between the first three scenarios (with a 2% difference between GPON over P2P unbundling as the first and WDM PON unbundling as the third). In contrast, the difference between WDM PON unbundling as the third and the two GPON bitstream scenarios is much larger (about 10%), while GPON bitstream core and GPON bitstream MPoP are almost equal. As explained below, the CS rankings are somewhat different in the No-Hinterland model and, except for the very close GPON over P2P unbundling and WDM PON unbundling scenarios in places 2 and 3, they are rather evenly spread.

In contrast to the case of CS, the rankings of W are similar between the Hinterland and the No-Hinterland model and so are the differences between Scenarios. There is a roughly 4% difference between the first (GPON over P2P unbundling) and the third (WDM PON unbundling) and a 7%-8% difference between third and 4th/5th place.

The difference in CS and W between Hinterland and No-Hinterland is greater than the simple addition of the cable market. A direct comparison of absolute values between the two models is therefore not appropriate.

In terms of W GPON over P2P unbundling ranks consistently first and narrowly beats P2P unbundling, while WDM PON unbundling is consistently third both for W and CS, usually with a significant margin. The margin is narrow for CS in the Hinterland model, because here WDM PON unbundling has 4 entrants, while P2P unbundling and GPON over P2P unbundling only have 3 entrants.

The two GPON bitstream scenarios are in a dead heat for last place in terms of W.

In terms of CS the ranking between the P2P topologies and between the GPON bitstream scenarios is reversed for the Hinterland and No-Hinterland model. In the No-Hinterland model there are only three entrants under GPON over P2P unbundling and four entrants under P2P unbundling. Vice versa, in the Hinterland model there are only 3 entrants under GPON bitstream MPoP and 4 entrants under GPON bitstream core. This leads to higher prices and lower CS for GPON over P2P unbundling than P2P unbundling and for GPON bitstream MPoP than GPON bitstream core.

Figure 2-19 and Figure 2-20 show that, in contrast to CS, W is not much affected by entry, once the number of firms reaches 4 (No-Hinterland model) or 5 (Hinterland model). Thus, as a result of different numbers of entrants, the same rankings of scenarios in terms of W are as unsurprising as are different rankings of scenarios in terms of CS. The small effect of entry beyond 4 or 5 firms on W seems to be the result of the stable market share of the incumbent. In the No-Hinterland case, the resulting cable's gain in market share relative to the entrants appears to be welfare neutral taking all other effects into account.

Figure 2-19: Welfare per month and number of competitors – GPON bitstream core, Hinterland

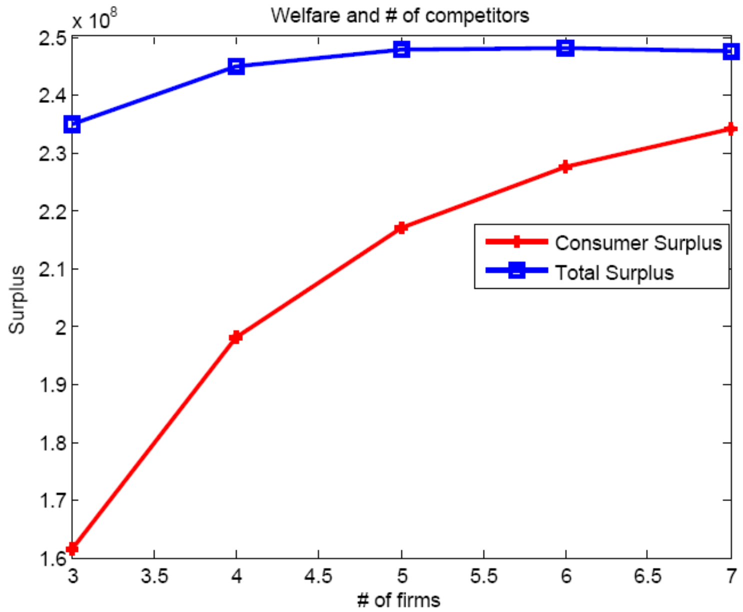
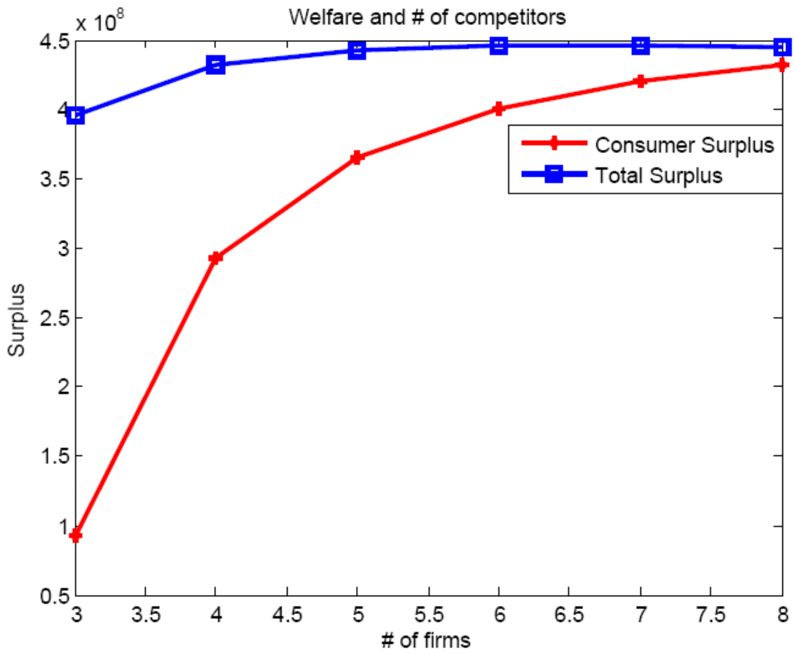


Figure 2-20: Welfare per month and number of competitors - GPON bitstream core, No-Hinterland



While W first increases in the number of firms, this ebbs off very quickly and possibly starts to decrease. In contrast, CS continues to increase fairly strongly in the number of firms.

Since the number of firms in equilibrium in some cases appears to be quite sensitive to small changes in model parameters (and therefore different between the Hinterland and the No-Hinterland model), the results on welfare should be considered more stable than the results on consumer surplus.

2.6.2.5 Access mark-up for the GPON bitstream core scenario

The GPON bitstream core scenario included “weak regulation” in its original definition. This has not been part of the basic model runs presented so far and will be done in the current section. In this context weak regulation shall mean that entrants have to pay a mark-up on the LRIC-based wholesale access charge. In the following we show the effects of such a mark-up of 0%-20% on prices, profits, market shares, CS and W.

While the presentation of results is restricted to GPON bitstream core, the results would be similar across all scenarios.

As expected and as shown in Figure 2-21 and Figure 2-22 a percentage mark-up on access charges leads to an almost parallel increase of all retail prices (incumbent, entrants and cable).

Figure 2-21: Prices and access mark-up - GPON bitstream core, Hinterland

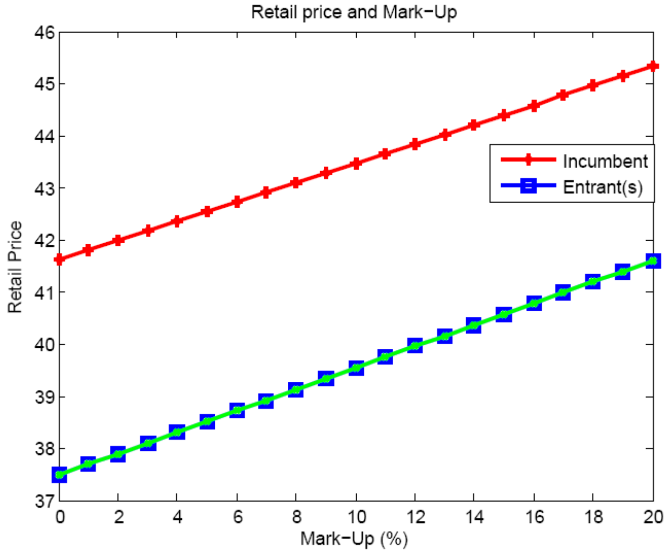
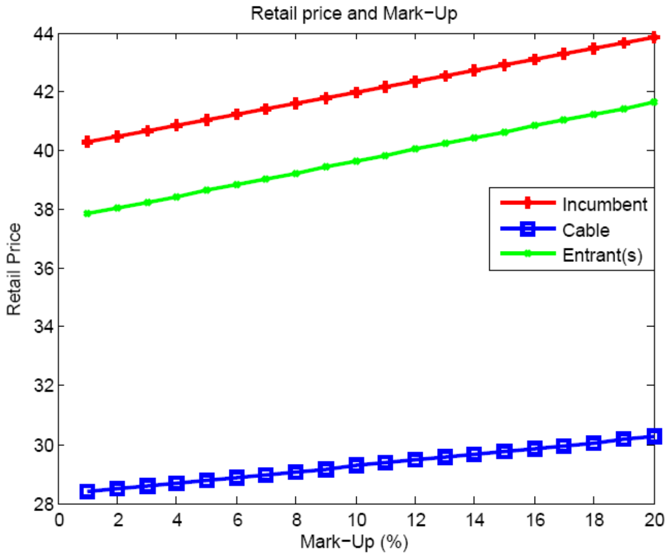


Figure 2-22: Prices and access mark-up - GPON bitstream core, No-Hinterland



As becomes clear from Figure 2-23 and Figure 2-24 the incumbent's wholesale profits increase strongly and linearly with an access mark-up. In contrast, the entrants' profits and the incumbent's downstream profits decrease very slightly with the mark-up. Cable's profits are again favorably affected by the mark-up, although not quite as much as the incumbent's overall profits.

Figure 2-23: Profits per month and access mark-up - GPON bitstream core, Hinterland

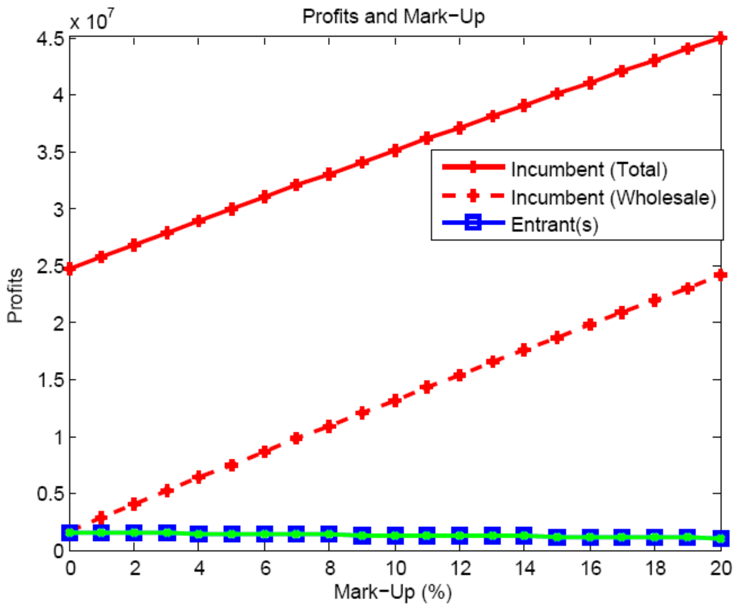


Figure 2-24: Profits per month and access mark-up - Scenario Bitstream access to GPON at core nodes, No-Hinterland

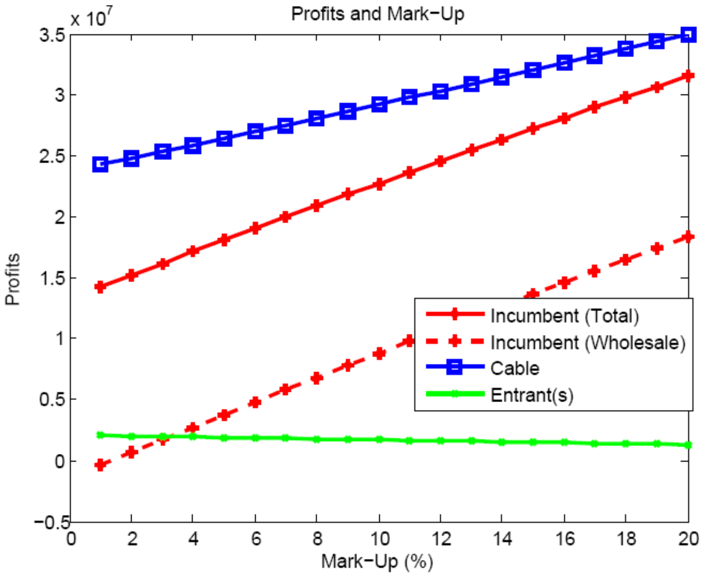


Figure 2-25 shows the incumbent's market share in the Hinterland model to increase slightly against entrants as a result of increased access charge mark-ups. In contrast, in the No-Hinterland model higher access charge mark-ups reduce the market share of entrants, hold the incumbent's market share constant and increase the market share of cable.

Figure 2-25: Market shares and access mark-up - GPON bitstream core, Hinterland

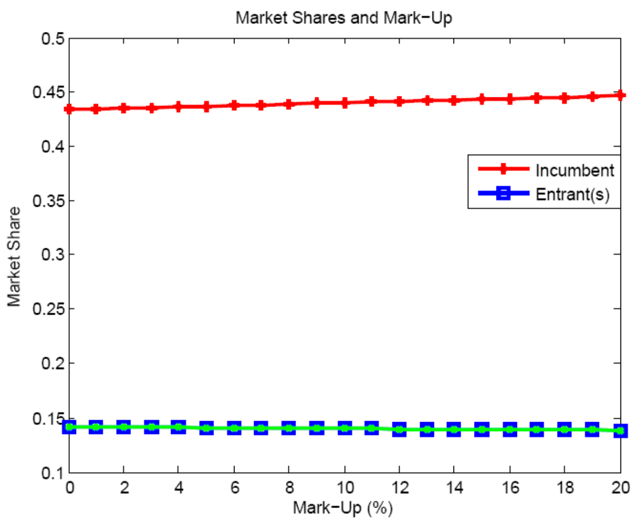


Figure 2-26: Market shares and access mark-up - GPON bitstream core, No-Hinterland

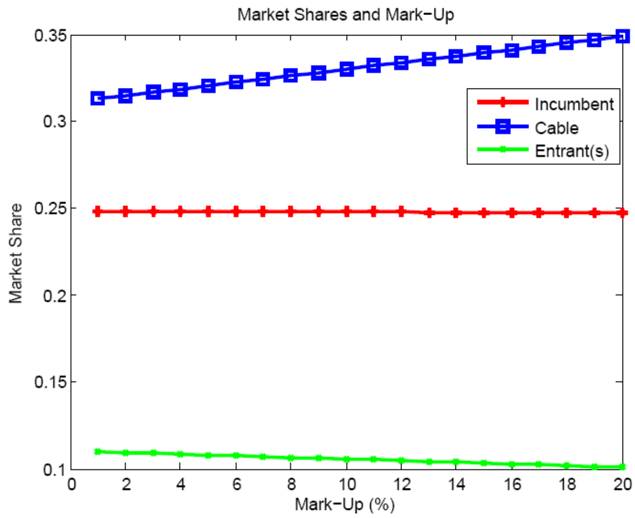


Figure 2-27 and Figure 2-28 show the relationship between access charge mark-ups and consumer surplus and welfare.

Figure 2-27: Welfare per month and access mark-up - GPON bitstream core, Hinterland

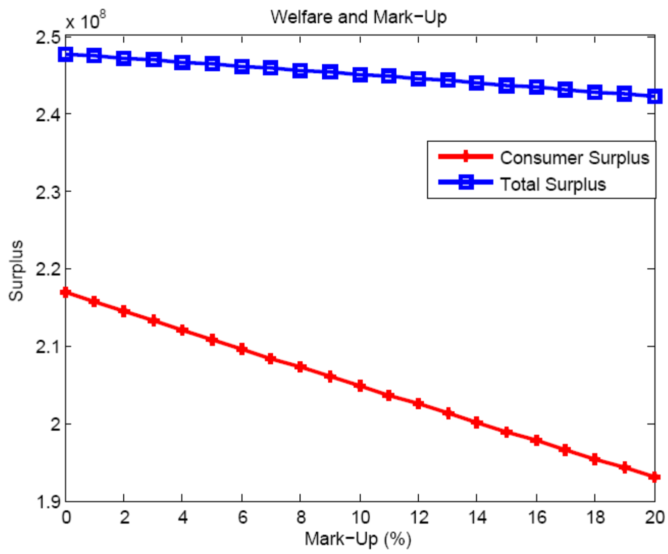
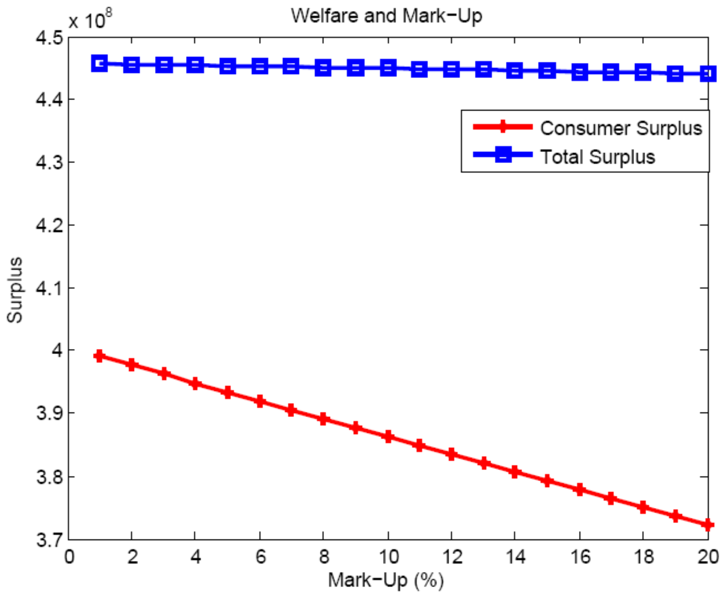


Figure 2-28: Welfare per month and access mark-up - GPON bitstream core, No-Hinterland



Both models show a weak decline in W and a strong decline in CS in an increase in access charge mark-up. Since incumbents' profits strongly increase and entrants' profits weakly decrease in the mark-up, such a mark-up may encourage incumbents' infrastructure investments. However, in our analysis so far incumbents' aggregate profits appear to be sufficient without mark-ups.

If we take weak regulation for the GPON bitstream core scenario to mean a 10% mark-up on LRIC wholesale access charges then weak regulation changes the rankings of the scenarios as follows. End-user prices are increased compared to the basic model run from 41.61€ to 43.46€ for the incumbent and from 37.48€ to 39.54€ for the entrants in the Hinterland model and from 40.10€ to 42.06€ for the incumbent and from 37.63€ to 39.82€ for the entrants in the No-Hinterland model. In both cases the incumbent's price ranking would move from lowest price (place 5) to highest price (place 1) for the incumbent and from place 5 to place 3 for the entrants. The incumbent's profits would increase by about 50% in both models, while the entrants' profits would decrease by about 15%. CS would decrease from 216.8 Mio € to 204.8 Mio € in the Hinterland model and from 400.5 Mio € to 384.5 Mio € in the No-Hinterland model. It would move the GPON bitstream core scenario from place 4 to place 5 in the Hinterland model and would reemphasize place 5 in the No-Hinterland model. In contrast, W would change very little, from 247.7 Mio € to 245.1 Mio € in the Hinterland model and from 445.7 Mio € to 444.3 Mio € in the No-Hinterland model. This would have no effect on the W-rankings. The results on wholesale access charge mark-ups in the competition models may appear to contrast with those of the critical market share analysis in the cost model (section 0).This is, because *critical market shares* of competitors increase in the cost model but *equilibrium market shares* remain relatively stable in the competition model. The current competition model assumes that demands for FTTH services are downward-sloping. Thus, an increased mark-up can be translated into a higher end-user price without too much loss in sales. In the cost model analysis the ARPU is taken as given and therefore implicitly assumes a horizontal demand curve at a price equal to the assumed ARPU. However, as long as the critical market shares determined in the cost model (which constitute minimum market shares for viability) remain below or at the level of the actual market shares in the competition model, there is no contradiction.[48]

2.6.2.6 Endogenous wholesale access charges

The wholesale access charges in our analysis are based on LRIC, which in turn is based on projected FTTH output quantities. In equilibrium the FTTH output quantities may differ from those projected quantities, requiring an adaptation of ‘a’ to the resulting new LRIC.

Annex 3 describes the formal method for calculating such adaptations for both the Hinterland model and the No-Hinterland model. This is done by solving for the LRIC corresponding to the actual equilibrium quantities of each case. We have done the calculations of endogenous access charges for all scenarios. As can be seen in Table 2-11 and Table 2-12 for the No-Hinterland case of the P2P unbundling scenario, the effect of endogenizing ‘a’ can be substantial. It is, however, strongest for P2P unbundling and GPON over P2P unbundling, where it leads to a substantial decrease in retail prices.[49]

In the P2P unbundling scenario, since the market share of cable with 22% is substantially below the 30% that we assumed for the LRIC calculation, the endogenized LRIC for access charges, based on 78% market share for FTTH, gives a reduction in the wholesale ULL charge from a = 21.14 to a = 19.82, corresponding to the exact equilibrium market share. As a result, all end-user prices are reduced, wholesale profits vanish (by construction) with a strong negative effect on the incumbent’s overall profits. Cable’s profits also decrease, while entrants’ profits rise moderately (not enough to spur further entry). Consumer surplus rises moderately and welfare only by a minimal amount.

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48 In addition, we have to keep in mind that market share's in the cost model are cluster-specific while market shares of the competition model are mostly based on an aggregated analysis of clusters 1-4.

49 In the first two scenarios in the No-Hinterland model the difference between exogenous and endogenous a is above 1.30 €, whereas for all other scenarios it is below 0.70 € and, in the cases of the bitstream access scenarios goes in the other direction.

Table 2-11: Basic model results P2P unbundling, No-Hinterland

	a = given = 21.14			
	General	Incumbent	Cable	Each Entrant
N	6			
P		42.07	23.76	42.37
Prof		18.78 Mio	2.81 Mio	0.45 Mio
WhProf		9.23 Mio		
S		0.23	0.22	0.14
sum(q)	8.64 Mio			
W	490 Mio			
CS	467 Mio			

Table 2-12: Model results with endogenous ‘a’, No-Hinterland, P2P unbundling

	a = endogenous = 19.82			
	General	Incumbent	Cable	Each Entrant
A				
N	6			
P		40.71	23.04	40.92
Prof		10.06 Mio	0.11 Mio	0. 81 Mio
WhProf		0		
S		0.23	0.21	0.14
sum(q)	8.64 Mio			
W	491 Mio			
CS	478 Mio			

2.6.2.7 Looking at Cluster 4 in isolation

Our analysis so far aggregates all variables and all results over the four densest population clusters of Euroland. This is based on the critical market share results of the cost model, which suggested that entrants and incumbents would be viable for all scenarios up to Cluster 4. This does not mean, however, that the viability of all firms, which was the basis of the free-entry equilibria presented so far, also holds for Cluster 4 in isolation. It may be doubtful because access charges, costs and end-user pricing have all been based on an aggregate (or average) of all four clusters. Cluster 4 as the marginal cluster with the lowest population density has higher fixed costs per user for all types of firms than the average of Clusters 1 to 4.

We have therefore, for P2P unbundling, separately calculated the relevant outcomes for Cluster 4 alone with a wholesale access charge based on

- the average of all four clusters: a = LRIC(Clusters 1-4) = 21.14
- the marginal Cluster 4: a = LRIC(Cluster 4) = 23.41
- the average of five clusters: a = LRIC(Clusters 1-5) = 22.85

The last case reflects the fact that, according to the cost model results, the incumbent would be viable in Cluster 5 as well as in Clusters 1-4. If the incumbent, in addition to Clusters 1-4, also penetrates Cluster 5 the LRIC relevant for wholesale access charges would therefore be based on the average LRIC of Clusters 1-5. This would follow currently used regulatory practice.

Table 2-13: Basic model results: Cluster 4 - P2P unbundling, Hinterland Model

Average access charge over 4 clusters: a = 21.14			
		Incumbent	**Each Entrant**
n	4		
p		46.32	44.87
Prof		2.52 Mio	0.69 Mio
WhProf		-3.02 Mio	
Cluster-specific access charge: a = 23.41			
n	4		
p		48.15	46.93
Prof		5.13 Mio	0.57 Mio
WhProf		-0.11 Mio	
Average charge Cluster 1-5: a = 22.85			
n	4		
p		47.70	46.43
Prof		4.50 Mio	0.60 Mio
WhProf		-0.81 Mio	

Table 2-14: Basic model results: Cluster 4 - P2P unbundling, No-Hinterland Model

Average access charge over 4 clusters: a = 21.14				
		Incumbent	**Cable**	**Each Entrant**
N	6			
P		42.07	23.76	42.37
Prof		1.08 Mio	0.67 Mio	-0.09 Mio
WhProf		-1.07 Mio		
Cluster-specific access charge: a = 23.41				
N	6			
P		44.01	24.77	44.42
Prof		3.88 Mio	1.65 Mio	-0.21 Mio
WhProf		1.90 Mio		
Average charge Cluster 1-5: a = 22.85				
N	6			
P		43.53	24.52	43.92
Prof		3.20 Mio	1.40 Mio	-0.18 Mio
WhProf		1.18 Mio		

When interpreting the results on Cluster 4 presented in Table 2-13 and Table 2-14, one has to keep in mind that Cluster 4 has 2,062,480 potential end-users compared to 8,636,068 potential users for all four clusters. Thus, as a separate market, Cluster 4 would have about 24% the size of all four clusters. Under the averaged access charge for all four clusters we get the same prices as before, but in the Hinterland model profits of the incumbent are only about 10% of the aggregate profits and profits of the entrants are only 18%. However, Cluster 4 remains profitable in isolation so that the equilibrium number of firms is reemphasized. One drawback for the incumbent is that wholesale access becomes a major loss maker and offering wholesale access therefore is not incentive compatible.

In contrast, incumbent's profits are only 6% of aggregate Clusters 1-4 profits and profits of entrants turn slightly negative in the No-Hinterland model. Thus, entrants may refrain from entering Cluster 4 in this case. Under cluster-specific wholesale access charges (a = 23.41) end-user prices increase but that only helps the incumbent, while entrants' profits/losses deteriorate. This pattern also holds for the not illustrated case of GPON over P2P unbundling.

Furthermore (not illustrated here), in the GPON bitstream scenarios and WDM PON unbundling the incumbent makes a loss on account of the larger wholesale loss associated with the smaller market share of FTTH relative to cable. Since only in the GPON bitstream core scenario the market share of FTTH is below the 30% assumed for the LRIC calculation relevant for determining the access charge, incumbent losses may turn up for all scenarios under endogenous access charges. This does not hold for the Hinterland model of P2P unbundling, where endogenous access charges of a = 20.94 lead to a slight reduction in the Cluster 4 incumbent's profit to 2.29 Mio € and an increase in each entrant's profits to 0.70 Mio €. However, in the No-Hinterland model with an endogenous access charge of a = 19.82 the incumbent generates an overall loss of 0.63 Mio € (resulting from a wholesale loss of 2.89 Mio €) and the entrants make a small loss of 0.02 Mio € each.

If the incumbent also serves Cluster 5 the resulting averaged wholesale access charge (a = LRIC(Clusters 1-5) = 22.85) leads to a result that lies between the result under a = 21.14 and under a = 23.41.

2.6.2.8 Cluster 5 results for the GPON bitstream core scenario

One of the results of the critical market share analysis has been that in the GPON bitstream core case both the incumbent and entrants could profitably operate in Cluster 5 as well as in Clusters 1-4. We have therefore done basic model runs of the GPON bitstream core scenario for the aggregate of Clusters 1-5 and of Cluster 5 in isolation. The access charge in this case is a = 23.77.

Table 2-15: Basic model run, Hinterland, GPON bitstream core, Clusters 1-5

	General	Incumbent	Each Entrant
n	5		
p		43.06	39.09
prof		28.91 Mio	1.84 Mio
WhProf		0.35 Mio	
s		0.44	0.14
sum(q)	7.79 Mio		
W	303 Mio		
CS	267 Mio		

Table 2-15 shows that both for incumbent and for the same number of entrants profits are higher for Clusters 1-5 than they were for the Clusters 1-4 case.[50] This results in spite of the higher Cluster 5 costs, because the higher access charge of a = 23.77 over the Cluster 1-4 access charge of a = 22.05 drove up end-user prices.

Table 2-16 provides the results for Cluster 5 in isolation, and it is quite surprising. Although adding Cluster 5 to Clusters 1-4 increases profits for both the incumbent and the entrants, Cluster 5 in isolation is a big loss maker for the incumbent, but provides decent profits for the entrants (considering that Cluster 5 has only about 22% the inhabit-

50 Profits are not higher in proportion to increased market size, though. However, since these profits are above the calculated rate of return on equity, their absolute size would be relevant for infrastructure investment.

ants of Clusters 1-5 together). The reason is that the incumbent's FTTH infrastructure access costs in Cluster 5 are 29.82 compared to the wholesale access charge of a = 23.77. As a result, the incumbent generates a wholesale loss of over 10 Mio €. Thus, the incumbent could have incentives not to invest in Cluster 5 if wholesale access seekers also enter. But nevertheless the incumbent would be better off than if he had only invested in Clusters 1-4.

Table 2-16: Basic model run, Hinterland, GPON bitstream core, Cluster 5 in isolation

	General	Incumbent	Each Entrant
N	5		
P		43.06	39.09
Prof		-3.91 Mio	0.50 Mio
WhProf		-10.32 Mio	
S		0.44	0.14
sum(q)	1.73 Mio		
W	57 Mio		
CS	59 Mio		

In Table 2-17 and Table 2-18 we show the same exercises for the No-Hinterland model. Compared to the Cluster 1-4 case the incumbent's profits are now about even for the aggregate of Clusters 1-5, while those of cable and entrants jump ahead. The reason is that the increased market price gives cable a boost, both in price-cost mark-up and in market share against FTTH. As a result, the incumbent suffers a substantial wholesale loss that negatively affects its overall profits.

Table 2-17: Basic model run, No-Hinterland, GPON bitstream core, Clusters 1-5

	General	Incumbent	Cable	Each Entrant
N	6			
P		41.65	29.14	39.38
Prof		13.44 Mio	33.25 Mio	2.56 Mio
WhProf		-5.24 Mio		
S		0.25	0.33	0.11
sum(q)	11.10 Mio			
W	555 Mio			
CS	498 Mio			

Table 2-18 shows that, again, Cluster 5 in isolation generates a huge wholesale loss for the incumbent, and that translates into a large overall loss as well.

Table 2-18: Basic model run, No-Hinterland, GPON bitstream core, Cluster 5 in isolation

	General	Incumbent	Cable	Each Entrant
n	6			
p		41.65	29.14	39.38
prof		-7.34 Mio	4.80 Mio	0. 66 Mio
WhProf		-11.56 Mio		
s		0.25	0.33	0.11
sum(q)	2.46 Mio			
W	110.55 Mio			
CS	110.44 Mio			

2.6.2.9 Basic model results: Conclusions

Although the two P2P topologies consistently show the highest prices, they also have highest levels of CS and W in the basic model runs. They are followed fairly closely by WDM PON and more distantly by the GPON bitstream scenarios. GPON bitstream core falls back even further if, for this scenario, strong regulation is replaced by weak regulation.

Sometimes the ranking of CS and W between scenarios do not coincide, mainly because of differences in the equilibrium number of firms. Since consumer surplus can be very sensitive to small parameter changes, the results on W are likely more robust than those on CS.

While CS always increases in the equilibrium number of firms, W is almost constant at the equilibrium levels reached in our model runs.

Under the basic parameterization in all scenarios only 3 or 4 entrants survive in equilibrium. This is the result of a combination of high cost and high WtP for some scenarios (notably P2P unbundling and GPON over P2P unbundling) and low cost and low WtP for others (notably GPON bitstream core and GPON bitstream MPoP). Independent of entry, the incumbent’s market share does not differ much across scenarios.

Because of lower costs incumbents are consistently profitable in the basic model runs, where entrants are profitable.

A percentage mark-up on the LRIC-based access charge leads to a corresponding increase in end-user prices of almost the same magnitude as the mark-up; entrants’ market share decreases and entrants’ profits decrease slightly, while the incumbent’s profits increase substantially.

Endogenizing the wholesale access charge strengthens the results of the basic model runs.

Profits in the marginal Cluster 4 are substantially lower than average profits for all Clusters 1-4. Because of large losses from selling wholesale access profits overall can turn negative for the incumbent and slightly negative for entrants, suggesting that the incumbent may refrain from entering Cluster 4 and fewer competitors may enter the marginal cluster than the others. This latter effect on competitors becomes stronger if one uses cluster-specific entry charges or if the incumbents also enters Cluster 5.

A competition analysis of Clusters 1-5 for GPON bitstream core showed that entering Cluster 5 would be profitable for entrants both on an aggregate basis and for Cluster 5 in isolation. However, such entry has ambiguous effects on the incumbent. The incumbent would have higher profits than if both he and the entrants would only enter Clusters 1-4. Yet, Cluster 5 in isolation would be a large loss maker. The reason is that overall prices increase through this expanded penetration, but it generates a large wholesale loss in Cluster 5.

The likely effect of wholesale access regulation on the incumbent's FTTH investment is therefore ambiguous, if applied a wholesale cost average. There seems to be no investment problem for an aggregate number of clusters. The incumbent's profits are sufficient for aggregate investments. However, there can be problems in the marginal clusters, where the incumbent's overall profits may turn negative on account of large wholesale losses. This would not happen if wholesale access charges were cluster-specific. But such differentiated charges could severely cut competitor entry in less densely populated clusters.

The main explanation for the welfare ranking for the Scenarios is the following: The rankings in terms of costs are almost exactly the reverse of the rankings of the scenarios in terms of consumer valuations. However, the cost differences are smaller than the valuation differences. As a result P2P unbundling and GPON over P2P unbundling rank ahead of WDM PON unbundling, which in turn beats the GPON bitstream scenarios.

2.6.3 Sensitivity analysis

In the following we show a few sensitivity analyses

- on cost assumptions, by contrasting a *Brownfield* approach with the *Greenfield* approach of the basic model
- on WtP for incumbent, entrant and cable services for all scenarios.

2.6.3.1 Greenfield vs. Brownfield results

Table 2-19, Table 2-20 and Table 2-21 contrast three cases. Table 2-19 shows the basic Greenfield results for WDM PON unbundling, while Table 2-20 gives Brownfield results based on LRIC cost calculations. Table 2-21 moves to stronger access charge regulation based on Brownfield costs. The cost change from Greenfield to Brownfield model only concerns the capital costs of FTTH access.

Since this does not affect LRIC and therefore LRIC access charges are unchanged, the effect of the Brownfield model leaves end-user prices and market shares unchanged. Only the incumbent's profit is increased by the cost saving. This is a well-known result from the theoretical literature.

However, if access charges are reduced by the cost savings end-user prices are reduced, market shares change little, profits of incumbent are slightly reduced but those of entrants increase (compared to the Greenfield approach).

Table 2-19: Basic Greenfield model results for WDM PON unbundling, Hinterland model, a = 21.24

	General	Incumbent	Each Entrant
n	5		
p		42.46	38.69
prof		23.05 Mio	1.83 Mio
WhProf		1.33 Mio	
s		0.414	0.147
sum(q)	6.24 Mio		
W	271 Mio		
CS	240 Mio		

Table 2-20: Brownfield model results for WDM PON unbundling, Hinterland model, a = 21.24

Brownfield, a = 21.43			
	General	**Incumbent**	**Each Entrant**
n	5		
p		42.46	38.69
prof		39.76 Mio	1.80 Mio
WhProf		18.03 Mio	
s		0.414	0.147

Comparing Table 2-19 and Table 2-20 shows that the only effect of moving from Greenfield to Brownfield is that the incumbent's wholesale profits increase precisely by the cost difference between the Greenfield and Brownfield models. However, if wholesale access charges are adjusted downward by the cost savings from a = 21.24 to a = 18.48 the end-user prices are lowered and profits for entrants increase (s. Table 2-21). The incumbent's profits are substantially lower than under LRIC access charges but still somewhat higher than under the Greenfield costs. Welfare increases almost exactly by the cost savings. Most of this increase benefits CS but some also goes to profits.

Table 2-21: Brownfield model results for WDM PON unbundling, Hinterland model, a = 18.48

Brownfield a = 18.48			
N	5		
P		40.32	36.32
Prof		26.72 Mio	2.12 Mio
WhProf		3.86 Mio	
S		0.408	0.148
sum(q)	6.37 Mio		
W	290 Mio		
CS	255 Mio		

As will be shown in section 3.2.3.3 below, a switch from PSTN to WDM PON can generate substantial liquidity for an incumbent from selling MDF locations in real estate transactions. This money would not have been available under continued use as MDF and therefore provides an additional profit potential generated by the switch to WDM PON. Since the net revenues from such real estate sales (exhibited in Table 3-34 below) only save capital costs, they can be treated almost exactly in the same way as the savings of the Brownfield over the Greenfield approach. For the clusters 1-4 modelled for our competitive analysis they would represent about 1.6% savings[51] over the Greenfield FTTH capital requirements or an increase of about 13% relative to the Brownfield cost savings for those four clusters. Without an adjustment of wholesale access charges the incumbent's profit under the WDM PON unbundling scenario would therefore increase by about an additional 2.2 Mio € per month. Alternatively, there could be an additional 0.40€ downward adjustment in the wholesale access charge to about a = 18.10€. This in turn would lead to a downward adjustment of end-user prices by about 0.30€ for both incumbent and entrants and to slight increases in profits for both types of firms compared to the Brownfield approach without sale of MDF locations.

Different from the Brownfield approach, however, is the welfare treatment of the savings from selling MDF locations. To the extent that the incumbent only exchanges one asset

51 We are using approximate figures here because of the inexact possibilities for discounting. The competitive model operates in a steady state about 10+ years from now. The savings may have to be brought up to that value, using the WACC, but that is not the way other costs are treated for steady state purposes. So, we have treated the savings like the other costs.

(real estate) against another (money) such a sale would be welfare neutral. The incumbent should have valued the opportunity cost of the real estate already under the PSTN regime. One can argue that dismantling the MDF has freed up the real estate and therefore created additional value, but that has also been associated with dismantling costs. So it is hard to squeeze extra welfare out of this transaction.

2.6.3.2 QoS and WtP assumptions

The following sensitivity analysis of our WtP assumptions is contrasting the basic Model (I) with three alternatives:

- **Model II.** An increase in the goodwill advantage of incumbents vis-à-vis entrants and cable by 3 € for all scenarios (from 2 € to 5 €). For our basic model we had assumed a small goodwill advantage of 2 € because we are modelling steady state competition ten years from now, when both incumbents and entrants are established FTTH suppliers. The reason for this sensitivity then is that today's goodwill advantage of incumbents appears to be larger than assumed in the basic model.

- **Model III.** A reduction in the spread between the different WtP for incumbents, entrants and cable for all scenarios by 50%. In our basic model we had assumed a fairly large spread between technologies based on expected ultra-high bandwidth requirements by a large fraction of users. Again, such large differentiation in WtP is not generally observable today.

- **Model IV.** First a reduction in the spread by 50% and then an increase in the goodwill advantage by 3 €. This model combines the properties of Models II and III.

- **Model V.** In addition, for WDM PON unbundling alone, we adapted the WtP closely to that of the GPON over P2P scenario. This model reflects uncertainties about the quality properties of WDM PON.

Table 2-22: WtP assumptions for sensitivity analysis

Scenario	I. Basic model			II. Increased incumbency advantage			III. Smaller spread			IV. Increased incumbency advantage and smaller spread		
	SI	SE	SC	SI	SE	SC	SI	SE	SC	SI	SE	SC
P2P unbundling	100	97	82	100	94	79	100	98.5	91	100	95.5	88
GPON over P2P unbundling	99	97	82	99	94	79	99.5	98.5	91	99.5	95.5	88
WDM PON unbundling	95	89	82	95	86	79	97.5	94.5	91	97.5	91.5	88
WDM PON unbundling alternative	99	95	82									
GPON bitstream core	90	83	82	90	80	79	95	91.5	91	95	88.5	88
GPON bitstream MPoP	90	85.5	82	90	82.5	79	95	92.75	91	95	89.75	88

We first present sensitivities for three scenarios, P2P unbundling, GPON bitstream core and WDM PON unbundling. The reason for this selection is that P2P unbundling benefits most from the high spread of the basic Model I. GPON bitstream core suffers most under the high spread. In contrast, in the basic Model I, WDM PON unbundling lies in between those scenarios and is closest in ranking to the two P2P topology scenarios. Also, only WDM PON unbundling is affected by the Model V changes.

Table 2-23 to Table 2-25, for the Hinterland case of each of the selected scenarios, compares the outcomes of the different models in terms of the equilibrium number of firms, prices, profits and market shares.

Table 2-23: Sensitivity to WtP assumptions - P2P unbundling, Hinterland Model

	WtP	n	p_I	p_E	$prof_I$ Mio €	$prof_E$ Mio €	s_I	s_E
I. Basic model	SI = 100 SE = 97	4	46.32	44.87	24.82	3.74	0.41	0.20
II. Increased incumbency advantage	SI = 100 SE = 94	4	47.35	44.30	29.05	2.43	0.44	0.19
III. Smaller spread	SI = 100 SE = 98.5	4	45.80	45.16	22.84	4.43	0.39	0.20
IV. Increased incumbency advantage and smaller spread	SI = 100 SE = 95.5	4	46.83	44.59	26.89	3.07	0.42	0.19

Table 2-24: Sensitivity to WtP assumptions – GPON bitstream core, Hinterland Model

	WtP	n	p_I	p_E	$prof_I$ Mio €	$prof_E$ Mio €	s_I	s_E
I. Basic model	SI = 90 SE = 83	5	41.61	37.48	24.67	1.54	0.43	0.14
II. Increased incumbency advantage	SI = 100 SE = 80	5	42.72	37.03	29.48	0.80	0.48	0.13
III. Smaller spread	SI = 95 SE = 91.5	6	38.92	36.36	19.72	0.35	0.36	0.16
IV. Increased incumbency advantage and smaller spread	SI = 95 SE = 88.5	5	41.71	37.69	26.79	1.91	0.42	0.14

Table 2-25: Sensitivity to WtP assumptions - WDM PON unbundling, Hinterland Model

	WtP	n	p_I	p_E	$prof_I$ Mio €	$prof_E$ Mio €	s_I	s_E
I. Basic model	SI = 95, SE = 89	5	42.46	38.69	23.05	1.83	0.41	0.15
II. Increased incumbency advantage	SI = 95, SE = 86	5	43.48	38.24	27.83	1.06	0.46	0.14
III. Smaller spread	SI = 97.5, SE = 94.5	6	39.76	37.39	17.07	0.33	0.36	0.13
IV. Increased incumbency advantage and smaller spread	SI = 97.5, SE = 91.5	5	42.59	38.75	24.34	1.95	0.41	0.15
V. Increased WtP for WDM PON	SI = 99, SE = 95	6	40.21	37.30	19.14	0.17	0.37	0.13

In comparison to the basic Model I we find the following for the Hinterland model:

In Model II (increased incumbency advantage) end-user prices, profits and market shares of the incumbent all increase at the expense of those of entrants.[52]

In cases where the number of firms stays the same, Model III (smaller spread) end-user prices, profits and market shares of the incumbent all generally decrease, while these variables increase for the entrants. However, in the GPON bitstream core and WDM PON unbundling scenarios the number of firms increases by one, leading to lower prices and profits for both types of firms. Such entry further erodes the incumbent's market share.

Model IV (increased incumbency advantage and smaller spread), as the intermediate case, shows almost the same prices, profits and market shares as Model I.

52 This result shows that the incumbent can have strong incentives to deteriorate the quality of the wholesale product provided to entrants.

Model V (improved WtP for WDM PON) for WDM PON unbundling leads to entry of an additional firm, implying substantially lower prices and profits. Market shares are quite similar to Model III.

Table 2-26 to Table 2-28, for the Hinterland case of each of the selected scenarios, compares the outcomes of the different models in terms of the equilibrium number of firms, prices, profits and market shares.

Table 2-26: Sensitivity to WtP assumptions - P2P unbundling, No-Hinterland Model

	WtP	n	p_I	p_E	p_C	$prof_I$ Mio €	$prof_E$ Mio €	$prof_C$ Mio €	s_I	s_E	s_C
I. Basic model	SI = 100 SE = 97 SC = 82	6	42.07	42.37	23.76	18.78	0.45	2.81	0.23	0.14	0.22
II. Increased incumbency advantage	SI = 100 SE = 94 SC = 79	5	46.62	45.40	27.26	32.00	6.17	10.52	0.28	0.16	0.23
III. Smaller spread	SI = 100 SE = 98.5 SC = 91	5	43.98	45.24	31.16	14.22	5.70	28.07	0.23	0.16	0.29
IV. Increased incumbency advantage and smaller spread	SI = 100 SE = 95.5 SC = 88	5	45.29	44.86	30.82	19.82	4.69	26.41	0.26	0.15	0.29

Table 2-27: Sensitivity to WtP assumptions – GPON bitstream core, No-Hinterland Model

	WtP	n	p_I	p_E	p_C	$prof_I$ Mio €	$prof_E$ Mio €	$prof_C$ Mio €	s_I	s_E	s_C
I. Basic model	SI = 90, SE = 83, SC = 82	6	40.10	37.63	28.28	13.22	2.07	23.72	0.25	0.11	0.31
II. Increased incumbency advantage	SI = 100, SE = 80, SC = 79	6	41.44	37.32	28.00	19.47	1.50	22.26	0.28	0.10	0.31
III. Smaller Spread	SI = 95, SE = 91.5, SC = 91	7	36.86	36.16	26.73	0.25*)	23.15	0.15	0.20	0.09	0.34
IV. Increased incumbency advantage and smaller spread	SI = 95, SE = 88.5, SC = 88	6	39.84	37.64	28.55	11.53	2.09	25.21	0.24	0.11	0.32

*) Large market share of cable leads to large wholesale loss. Endogenous ‘a’ would fix that.

Table 2-28: Sensitivity to WtP assumptions - WDM PON unbundling, No-Hinterland Model

	WtP	n	p_I	p_E	p_C	$prof_I$ Mio €	$prof_E$ Mio €	$prof_C$ Mio €	s_I	s_E	s_C
I. Basic model	SI = 95 SE = 89 SC = 82	6	41.24	39.32	26.16	17.91	2.92	13.09	0.24	0.12	0.27
II. Increased incumbency ad-vantage	SI = 95 SE = 86 SC = 79	6	42.59	39.01	25.89	24.07	0.23	11.83	0.28	0.11	0.27
III. Smaller Spread	SI = 97.5 SE = 94.5 SC = 91	7	37.97	37.53	25.93	2.34	0.29	18.60	0.19	0.10	0.32
IV. Increased incumbency ad-vantage and smaller spread	SI = 97.5 SE = 91.5 SC = 88	6	40.99	39.04	27.77	13.03	2.34	21.06	0.24	0.12	0.30
V. Increased WtP for WDM PON	SI = 99 SE = 95 SC = 82	7	39.01	38.09	21.42	18.84	1.30	-2.35	0.22	0.11	0.22

In comparison to the basic Model I we find the following for the No-Hinterland model:

In cases where the equilibrium number of firms stays the same, Model II end-user prices, profits and market shares of the incumbent all increase at the expense of entrants, while the results for cable are generally unchanged. In the first scenario the number of firms is decreased by one, leading to higher prices and profits for all firms. In this case the market share of the incumbent and cable increase at the expense of entrants.

Model III (smaller spread) shows very differentiated results, depending on whether the number of entrants decreases, (P2P unbundling) or increases (GPON bitstream core and WDM PON unbundling).

In the P2P unbundling scenario the number of firms decreases by one, leading to higher prices for all firms. Profits of cable and entrants increase, while those of the incumbent drop. In this case the market share of the incumbent remains the same, while cable increases at the expense of entrants.

In GPON bitstream core and WDM PON unbundling the number of firms increases by one, leading to lower prices and profits for incumbents and entrants, while those of cable increase substantially. Such entry erodes the incumbent's market share in favor of cable.

With the exception of P2P unbundling Model IV (increased incumbency advantage and smaller spread), as the intermediate case between Models II and III, shows almost the same prices, profits and market shares as Model I. In the P2P unbundling scenario

Model IV has one less firm than Model I, leading to higher prices and profits for all firms. The incumbent and cable gain market shares at the expense of entrants.

Model V (improved WtP for WDM PON) leads to entry of an additional firm, implying substantially lower prices and profits. The incumbent and cable lose market shares.

Table 2-29 to Table 2-32 relate the WtP assumptions of Models I-V to the CS and W outcomes across all scenarios.

Table 2-29: Sensitivity to W and CS to WtP assumptions Hinterland Model, in Mio Euro

	P2P unbundling		GPON over P2P unbundling		GPON bit-stream core		GPON bit-stream MPoP		WDM PON unbundling	
	CS	W	CS	W	CS	W	CS	W	CS	W
Basic model	243	279	246	284	217	248	209	245	240	271
WDM PON alternative									281	301
Increased incum-bency advantage	233	269	236	274	206	239	199	236	230	262
Smaller spread	248	284	252	290	268	289	263	283	277	296
Increased incum-bency advantage and smaller spread	238	274	241	280	231	273	231	273	253	286

Table 2-30: Sensitivity to W and CS to WtP assumptions Hinterland Model, ranking

	P2P unbundling		GPON over P2P unbundling		GPON bitstream core		GPON bit-stream MPoP		WDM PON unbundling	
	CS	W	CS	W	CS	W	CS	W	CS	W
Basic model	2	2	1	1	4	4.5	5	4.5	3	3
WDM PON alternative	3	3	2	2	4	4.5	5	4.5	1	1
Increased incumbency advantage	2	2	1	1	4	4.5	5	4.5	3	3
Smaller spread	5	4.5	4	2	2	3	3	4.5	1	1
Increased incumbency advantage and smaller spread	3	4	2	2	4.5	4	4.5	4	1	1

Table 2-31: Sensitivity to W and CS to WtP assumptions No-Hinterland Model, in Mio Euro

	P2P unbundling		GPON over P2P unbundling		GPON bit-stream core		GPON bit-stream MPoP		WDM PON unbun-dling	
	CS	W	CS	W	CS	W	CS	W	CS	W
Basic model	467	490	434	494	400	446	416	445	431	474
WDM PON alternative									490	513
Increased incum-bency advantage	410	471	413	474	380	428	360	426	411	456
Smaller spread	454	513	457	517	489	513	478	507	500	522
Increased incum-bency advantage and smaller spread	434	494	437	498	448	493	422	487	459	503

Table 2-32: Sensitivity to W and CS to WtP assumptions No-Hinterland Model, ranking

	P2P unbundling		GPON over P2P unbundling		GPON bitstream core		GPON bit-stream MPoP		WDM PON unbundling	
	CS	W	CS	W	CS	W	CS	W	CS	W
Basic model	1	1.5	2.5	1.5	4	4.5	3	4.5	2.5	3
WDM PON alternative	2	2.5	3.5	2.5	4	4.5	4	4.5	1	1
Increased incumbency advantage	2.5	1.5	1	1.5	4	4.5	5	4.5	2.5	3
Smaller spread	4.5	3	4.5	3	2	3	3	5	1	1
Increased incumbency advantage and smaller spread	3.5	3.5	3.5	1.5	2	3.5	5	5	1	1.5

Compared to the basic model (Model I):

An increase in the incumbency advantage (Model II) leaves the rankings with respect to CS and W largely intact. CS and W generally decrease because of the lower WtP for entrants' and cable services.

A decrease in the spread of WtP (Model III) changes the CS ranking against the two P2P topology scenarios. WDM PON emerges as the first-ranked and GPON bitstream core as second.[53] The change in rankings is less pronounced for W, but WDM PON unbundling is again first. CS and W increase in all cases, due to the implied higher WtP for all scenarios.

53 The ranking of Scenario 3a could be negatively affected by replacing strong with weak regulation.

Model IV leads to the most even levels of CS and W under all scenarios. WDM PON unbundling again comes out ahead.

Model V only changes the ranking of WDM PON unbundling by moving it ahead of the P2P topologies scenarios.

2.6.3.3 Conclusions on sensitivities

The sensitivity analyses have added the following to the basic conclusions:

Moving from a Greenfield approach to a Brownfield approach for the incumbent's FTTH investments affects (and increases) competition only if the regulator deviates from LRIC pricing of wholesale access. Profits of the incumbent are increased even if the whole-sale access charge is adjusted downward.

Changes in the WtP assumptions can have substantial effects on the model results.

However, results of the basic model are reemphasized for the most likely alternative to the basic model, which is to increase the incumbency advantage (Model II).

The next realistic alternative (Model IV) provides very similar market outcomes to the basic model, but leads to different rankings in the valuations of CS and W.

The least realistic alternative (Model III) changes many outcomes.

An adaptation of WtP for the WDM PON unbundling scenario to those of GPON over P2P unbundling (Model V) leads to a reversal in the CS and W ranking between the P2P topology scenarios and WDM PON unbundling.

Rather than coming up with an unambiguous winner the competitive analysis has revealed some consistency along with major tradeoffs. Considering the consistency of CS and W rankings of individual scenarios across models WDM PON unbundling always comes up among the best, while GPON bitstream MPoP always is among the lowest-ranked. P2P unbundling shows a highly variable ranking, but is usually in the first tier. GPON over P2P unbundling is also quite variable but mostly ahead of P2P unbundling. GPON bitstream core is as variable as P2P unbundling, but shows up mostly in the second tier and would rank even worse under weak regulation. The main explanation for the lack of consistency in ranking for P2P unbundling, GPON over P2P unbundling and GPON bitstream core scenarios lies in the fact that the rankings in terms of costs are almost exactly the reverse of the rankings of the scenarios in terms of consumer valuations. For given cost differences any changes in the valuations therefore can have large effects on the net results of valuations minus costs.

3 Opex and capex of different FTTH technologies

3.1 The modelling approach

3.1.1 General approach

Our basic modelling relies upon an engineering bottom-up cost modelling approach. This means we model the total cost of the services considered under efficient conditions, taking into account the cost of all network elements needed to produce these services in the specific architecture deployed. This approach is coherent with an (LRIC) approach as applied in regulatory economics.

Our model consists of a static and a dynamic approach. In the static model we compare the cost of a specific NGA deployment in a steady state in the future. In the steady state the roll-out is completed and the FTTH network has (fully) substituted the copper access network. By increasing the market share and comparing the resulting cost per customer with the fix revenue per customer we determine the point, where, if at all, the revenue equals the cost. This is the “critical market share” necessary to make the NGA business profitable and hence it determines the viability range of a network operator. Therefore we model the complete value chain of the operators. Contrary to the steady state model the dynamic approach considers the time path of investment according to a particular roll-out as well as the re-investment pattern. This methodology is explained in more detail in section 3.1.8 and only covers the expenses/cost side of the business.

The critical market share may not exceed a dedicated percentage of the potential subscriber base. In the telecommunications market all fixed network operators together will never achieve 100% market share since there are always potential subscribers who are not willing to use a fixed NGA network, but instead favor the use of a mobile network only, the use of a cable-TV network or even do not use telecommunication access at all. Thus, we believe the maximum achievable market share of an FTTH network of all potential subscribers is in the range of 70% for Euroland, which is the lower level of the fixed network market share in most European countries today.

According to the chosen LRIC approach we calculate the cost of each of the four architectures considered following a Greenfield approach. This means that the investor will construct a new, efficient state of the art network from scratch, assuming that currently existing infrastructure, if included in the new network, has to be considered at (full) cost. However, in reality there often is available infrastructure from legacy networks which may be reused for NGA to generate investment savings. This possibly could have an impact on the investment decision. We analyze this aspect in a sensitivity calculation carried out later on in section 0 as "Brownfield deployment".

With WDM PON many of the MDF locations are no longer used but replaced by larger manholes to host the additional splitters. These MDF locations may be sold. For this purpose they have to be dismantled and the technical installations have to be removed, thereby reducing the net proceeds of selling MDF locations. For an incumbent investor's decision the net dismantling lump sum revenues may be a relevant element of his decision process. Since these revenues are not part of the relevant cost, nor do they in fact reduce cost, we consider these revenues and their influence on the total ranking of the different solutions in the dynamic model within the net present value calculation (section 3.2.3) and also in the competition model influencing the incumbent's profit (see section 2.6.3.1).

3.1.2 Geotypes of Euroland

The viability of access networks strongly depends on the subscriber density (subscribers per km²) and on settlement structures. The denser the subscribers, the sooner the access network will become viable. Thus the modelling has to rely upon a concrete settlement structure, a given country, and the results derived depend on that country.

For purpose of this study we decided not to choose a dedicated European country but chose a settlement structure which is typical for European countries and to design the hypothetical country for approximately 22 million households or a population of around 40mn inhabitants. This country is referred to as "Euroland". We have defined 8 clusters, each having typical structural access network parameters derived from detailed geo-modelling of access networks in several European countries on a nationwide basis. The geotypes characteristics rely on exact data from several countries. In that sense, Euroland is a generically representative country.

Each of the 8 clusters is characterized by specific subscriber densities. The viability of a specific business model is calculated for each cluster separately, like for a separate profit center, i.e. the viability of a business model in Cluster 1 is independent from the viability in Cluster 2. In each of the clusters we assume the access network to be rolled out to 100% homes connected. For each of the clusters, the point where the NGA business may become viable is calculated individually and independently from the results of other clusters. The operators (incumbent and entrants) invest in all clusters which are viable.

The clusters are composed in a way that they address similar numbers of potential subscribers. Table 3-1 provides an overview of the resulting cluster classification.

Table 3-1: Structural parameters of Euroland

Geotype	Cluster ID	Potential customers per km²	Total potential customers per cluster	Share of total customers	Potential customers (cumulated)	Number of MDF	Potential customers per MDF	Average trench length per potential customer (m)
Dense urban	1	4,000	1,763,916	8%	1,763,916	69	25,564	2.4
Urban	2	1,600	2,163,672	10%	3,927,588	168	12,879	5.4
Less Urban	3	800	2,646,000	12%	6,573,588	252	10,500	7.8
Dense Suburban	4	470	2,062,480	9%	8,636,068	280	7,366	10.2
Suburban	5	280	2,460,360	11%	11,096,428	303	8,120	13.1
Less Suburban	6	150	2,989,056	14%	14,085,484	417	7,168	17.4
Dense Rural	7	60	4,331,208	20%	18,416,692	1,421	3,048	28.6
Rural	8	< 60	3,448,368	16%	21,865,060	2,488	1,386	55.1
			21,865,060	**100%**		**5,398**		

The steady state model will run for all 8 clusters described in Table 3-1. Typically in the dense clusters there are larger MDF locations concentrating significantly higher numbers of potential subscribers than in the rural areas, thus with 28% of the MDF one can already cover 64% of the potential subscribers (Cluster 1–6).

The clusters are mainly used to consider the cost differences due to the different geographic and settlement information. We use cluster-specific individual input data for access line length and DP sizes, for construction cost and for deployment methods (e.g. underground ducted, buried or aerial cabling). Main cluster specific values are the construction cost of ducts/cables, manholes, sleeves and aerial cables and the inhouse cabling. Construction costs are highest in the densely populated areas, while aerial cabling is used to a larger degree in the rural areas.

Table 3-2: Aerial deployment share per cluster

Cluster ID	Aerial share
1	0%
2	0%
3	10%
4	20%
5	30%
6	40%
7	60%
8	60%

Identical for all clusters are the values for MPoP components like Ethernet switches/ ports, OLTs, ODF ports and patch cables and fibre splices and also the values for fibre cables and CPE.

Result of this approach is the viability of each of the clusters, which allows one to determine the profitable reach of a market approach on a per cluster level (independent from other clusters).

3.1.3 Network structure

The network modelled consists of a core network, a concentration network and one of the next generation access network architectures as described in section 2.3.

For sake of modelling simplicity we have chosen existing core and concentration network bottom-up LRIC models for several countries which we adapted to the Euroland circumstances concerning business and residential end customers and their data volumes transmitted.

According to the defined size of Euroland the core network consists of 45 core layer nodes where core routers are located. These are Label Edge Routers (LER) for managing the access and Label Switch Routers (LSR) for managing a fast switching of the IP data packets. At five locations we also assume IP core backbone layer functions of additional LSR, building the upper network layer and reducing meshing complexity of a 45 location core network. We do not model the core network explicitly but describe it as a cost function with a fixed fee element and variable cost per customer (usage-based).The cost curve is derived from existing bottom-up models as described above. The core network is the same for all access architectures considered. Since the cost share of the core network is small compared to the total cost and the absolute cost is the same for all architectures, we regard this approach as a reasonable approximation for our comparative results.

The concentration network bridges the gap between the MDF locations (MPoPs) and the core layer nodes. We assume it to consist of state of the art Ethernet switches. Also these cost have been derived as a cost function of fixed cost plus usage (customer) dependant variable cost from an existing model which has been scaled for Euroland. The cost share of the concentration network is small compared to the access network cost. Thus, we are convinced that proceeding in this way is reasonable. For WDM PON the concentration network is replaced by a passive backhaul network.

The fixed cost of the national core and concentration network is distributed to the clusters by defining a fixed share for each cluster and distributing the remaining fixed cost according to the number of node locations (MPoP) per cluster.

The main cost of these NGN/NGA architectures is borne by the access network, especially by the civil engineering cost of digging trenches etc. The different NGA networks therefore are modelled in detail in a bottom up manner

The bottom-up modelling requires calculating the network cost item per item, considering each fibre per end customer, the splices, manholes and ODF ports needed, cable sizes and optimal trench sizes, space and energy requirements etc. All these items are considered according to the architectural solutions described in section 2.3.

3.1.4 The incumbent as investor

We consider two different types of players in the NGA market:

- An incumbent as investor
- A competitive entrant as wholesale access seeker.

The incumbent may deploy his NGA network in one of the above described technical architectures (GPON, P2P, GPON over P2P or WDM PON). The investor will roll out the NGA network to those areas (clusters) where the business will be viable, in a Greenfield approach.

The wholesale access seeker does not need to construct all infrastructure on his own, but could use the access network from the incumbent. Thus, the competitor can enter the market either by fibre unbundling, or by using bitstream access at MPoP or at core level. We assume the retail price a competitor may achieve for his services to be less than the price for the investor by 5%.

3.1.5 Demand

The model applies an average subscriber with a demand of about 400kbps capacity in the busy hour of the day and an Average Revenue Per User (ARPU) of 44.25€ per month. This is based on the customer mix of

- single play (voice only),
- double play (voice and broadband),
- triple play (voice, broadband and IPTV) and
- business users (mix of voice, broadband internet and VPN)

as shown in Table 3-3. Compared to previous studies by WIK this is a relatively high ARPU as we generally argue that ARPUs will not substantially increase through the transition to the NGA. The reason for a higher ARPU is that in this model the operator has borne the cost of inhouse cabling and the CPE and we assume that he will price the service accordingly to at least cover (some of) this cost. The assumed ARPU is the same for all considered architectures.

Table 3-3: Customer mix

	Traffic in the Busy Hour per subscriber (in kbps)	Revenue per subscriber (in €)	Share of subscribers
Voice only	20	17	5%
Voice and Broadband	380	36	25%
Voice, Broadband and IPTV	425	44	60%
Business customer	600	80	10%
Average user	411	44.25	100%

When analyzing the wholesale access scenarios we have decreased the ARPU of competitors by 5% to 42.04 € per month reflecting the incumbency advantage of e.g. brand and customer base. Also in the competitor case this ARPU remains the same regardless of the considered scenario (e.g. P2P unbundling or GPON bitstream). The ARPU of the static and dynamic modelling approach is used to determine the competitive edge of the scenarios, the critical market share and the viable clusters. We will develop a more sophisticated demand approach in the oligopoly modelling for determining the competitive results.

3.1.6 Major assumptions on capex and opex

3.1.6.1 Capex

The cost model annualizes the investment positions derived in a bottom-up manner by multiplying them with the corresponding capital cost factor. This factor is specified according to the tilted annuity formula which takes into account the WACC (Weighted Average Cost of Capital) as relevant interest rate, the economic lifetime and the average relative price change that is to be expected over the considered time period. It is expressed as follows:

$$CCF = \frac{WACC - PC}{1 - (\frac{(1+PC)}{(1+WACC)})^n}$$

where n = economic lifetime of network element and PC = expected price change of the equipment.

The model considers as additional investment positions assets that are not directly, but indirectly assigned to the network deployment, such as motor vehicles, office equipment, land and buildings etc. These positions are considered as mark-ups to be applied to the (direct) investment calculated for the network deployment. The factors are input parameters and are set for each direct investment position separately, e.g. trenches, manholes, sleeves etc. This indirect investment is then assigned to the modelled network deployment and annualized to yearly indirect cost (indirect CAPEX) by multiplying it with the Capital Cost Factor described above.

The multiplication of the investment positions with the capital cost factor results in annualized direct and indirect capital cost (CAPEX). Economic lifetimes are considered separately for all investment components required directly or indirectly for the network deployment. For the passive infrastructure from customer’s premise to MPoP we assume the economic lifetime to be 20 years, for active equipment in the MPoP (OLTs, Ethernet switch ports) 7 years and 5 years for the CPE unit. We assume a WACC of 10% to be adequate for the scenarios considered taking into account the risk of deploying a fibre network. In all our calculations introduced in this report price changes are set to zero.

3.1.6.2 Opex

In addition, the model considers costs resulting from operating the network and carrying out regular maintenance works (OPEX). In general, these costs are calculated as a mark-up which is applied to the direct and indirect investment positions, distinguishing between passive (0.5% mark-up) and active equipment (8% mark-up). For aerial cables we assume a higher OPEX mark-up (15%) than for cables deployed in ducts since aerial cables are more sensitive to damages and require more maintenance. However, they are less investment intensive than duct cables so that this mark-up is applied to relatively low values.

The model determines the cost of energy and floorspace rental in a bottom-up manner. Based on discussions with equipment vendors we have assumed average energy consumption on a per port per month basis. We can therefore easily track cost of energy in the MPoP through the number of ports required. Energy consumption per port is higher for WDM PON than for GPON OLTs and higher for 10 Gbps Ethernet ports than for 1 Gbps ports. We have not tracked the energy consumption of CPEs because the subscribers bear energy cost themselves. From a “green IT” or macro-economic point of view it would be important to also take CPE energy cost into account when comparing technologies, since more power consuming technologies at the central site are less power consuming at the end customer sites (e.g. Ethernet P2P). We have only focused on the operator case.

Regarding floorspace we have made assumptions on the number of ports (ODF, Ethernet, OLT) that fit into a standard 2 m² footprint rack based on feedback from equipment vendors. ETSI racks are considered to be deployed back to back. Equipments (OLT, Splitter, Ethernet switch, …) do not share racks, so rack space is tracked separately for each equipment port type. In the case of GPON and WDM PON rack space in the MPoP is predetermined by the assumption of 100% coverage in a cluster because this also determines the number of network sided ODF ports, OLTs and PON (upstream) Ethernet Ports. Contrarily, in case of P2P and GPON over P2P the network sided ODF ports and the active electronics – and hence the required rack space - depend on the number of subscribers. It was assumed that the incumbent plans his floorspace according to a 70% take-up on his network (retail and wholesale customers). In addition to the rack-dependent floorspace 30 m² per MPoP have been considered as base floorspace needed for office, restrooms, circulation areas etc. equally for all architectures. Having determined the required floorspace in m² we assume both an initial investment per m² to set-up the room (1000€) and a monthly rental cost per m² (20€).

A “retail cost” of 5€ per subscriber per month was assumed. These costs cover customer acquisition, sales and marketing, customer care and billing. We believe this to be at the lower end of such costs at least if compared with today’s market level.

Finally, a common cost mark-up of 10% is applied to the sum of operational and capital expenses. Common costs are expenses for positions which are not directly involved with the network, but which are needed for other processes of the enterprise. Among others management, administration, human resources and strategy and research (overheads) are positions which are part of these costs.

3.1.7 Wholesale cost and prices

Wholesale prices for the competitor's business case have been determined as LRIC (Long Run Incremental Cost) of the network elements of the incumbent which are used for wholesale access, i.e. they directly base on the cost determined for the incumbent. Since a significant part of costs is fix the total cost per customer strongly depends on the number of customers on the incumbent's network. Wholesale prices have been determined under the assumption that the incumbent's network operates at a 70% take-up. This rate corresponds to the market share of the FTTH network against the competition of mobile and cable networks.[54] This also means that these are the lowest possible wholesale prices under the LRIC assumptions. Depending on the scenario, they include active equipment in the MPoP (e.g. scenario GPON with bitstream access at MPoP) or even transport through the incumbent's concentration network (e.g. scenario GPON with bitstream access at core layer). Section 2.3 explains the components in more detail. The cost of the optical inhouse cabling is also part of the wholesale charge. All analysis is cluster-specific, so the wholesale price in Cluster 1 is independent from the wholesale price in other clusters.[55]

Wholesale prices used in this cost model to calculate the business model of a competitor are always a fixed monthly access charge per user per month (linear access charge). On top of the LRIC network cost per customer a wholesale cost of the incumbent's wholesale division is applied to determine the access charge for wholesale access seekers. This wholesale division cost was assumed to be 0.90€ per user per month (less than 20% of the assumed retail cost that incumbent and competitors both spend for each subscriber).

The primary analysis assumes a Greenfield deployment of NGA in which the network is built from scratch. We do however also do a sensitivity run, in which the incumbent benefits from existing duct infrastructure and reduces his investments. Under this sensitivity we have calculated a case in which competitors buy wholesale at Greenfield LRIC and a case in which Brownfield LRIC are the basis of the competitors' wholesale price inputs. The results can be found in section 0.

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54 The corresponding share in Germany of the fixed network today amounts to about 80% of potential subscribers.

55 In the competition model an average of the first 4 clusters has been chosen and discussed.

3.1.8 Dynamic approach

In the steady state analysis we do not consider the ramp-up period that is required to first deploy the network and then to acquire customers until the market reaches a steady state and the copper network is fully substituted. Significant investments are required upfront, e.g. all civil works which is why investment peaks relatively early. Architectures exhibit differences in their investment profile over time which could have an impact on their ranking in relative financial performance. For example, while P2P generally is the most expensive solution it allows one to spread investments in active electronics better over the course of actual subscriber acquisition than GPON. In order to analyse this we have modelled a successive deployment in “Euroland’s” first six clusters because these have shown to be profitable for at least some of all four architectures (the two rural geotypes have not been run through the dynamic model extension). The dynamic analysis is more inclined to model the actual deployment over large parts of a country consisting of different clusters.[56] We have analysed investments and costs over a period of 20 years (no revenues were taken into account) to assess the relative performance of architectures. So we have only looked at the investor’s side in this analysis and not at the wholesale access seeker’s.

3.1.8.1 Network roll-out

To define the time-path of the FTTH roll-out we have assumed that an operator would have restrictions on the operational resources for deploying FTTH (e.g. civil works subcontractors) that limit him to a maximum capacity of 2mn passed homes per year. We have assumed that he will focus deployment on the three densest and most profitable clusters initially and use any remaining capacity as it becomes available to deploy clusters 4-6. As a result the operator has the deployment path that is shown in Table 3-4. Deployment in clusters 1-4 commences in year 1 and ends between year 3 (Cluster 1) and year 5 (Cluster 4). Only when these dense clusters have been passed does deployment in clusters 5 and 6 begin. The deployment in all six clusters is completed after 8 years passing about 14mn homes.

56 In the steady state analysis the results are primarily “stand-alone” cluster-specific.

Table 3-4: Deployment of FTTH in Euroland (passed homes per year)

Cluster	Total customer base	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
1	1,763,916	600,000	600,000	563,916					
2	2,163,672	600,000	600,000	600,000	363,672				
3	2,646,000	600,000	600,000	599,400	846,600				
4	2,062,480	200,000	200,000	236,684	789,728	636,068			
5	2,460,360					1,363,932	1,096,428		
6	2,989,056						903,572	2,000,000	85,484

Again, the deployment path is the same for all architectures. However, there are differences in how active electronics are deployed over time: In the case of GPON and WDM PON OLTs have to be deployed together with the roll-out of the passive network. This means that e.g. a GPON OLT is deployed in the MPoP for every 64 homes passed[57] and - since initially only 10% of homes are acquired - will run at a relatively low efficiency initially. Contrarily GPON over P2P will deploy one OLT for every 64 acquired subscribers[58] and will hence operate at a higher level of efficiency even at low penetration levels.

3.1.8.2 Subscriber acquisition

Acquisition of subscribers is modelled on the basis of a generic penetration that grows relatively quickly to a 70% take-up within 5 years. Every year that new homes passed are added, penetration starts at 10% for these homes and grows to 70% over 5 years. This means that the total roll-out area of e.g. Cluster 1 will have reached an overall take-up of 70% at the end of year 7 in which the homes passed in year 3 have reached said target penetration. Considering all six clusters of Euroland, the ramp-up is concluded in year 13 when all clusters have reached 70% penetration.

Table 3-5: Evolution of take-up rate in the dynamic model

Year of service availability	1	2	3	4	5
Take-up rate	10%	20%	40%	60%	70%

3.1.8.3 Replacement investments and price adjustments

We have considered replacement investments for all network elements within the 20 year period. All equipment prices and costs have been set constant, so replacement investments occur at the level of the initial investment and direct costs such as retail cost remain at the same level throughout the 20 year period.

57 Since we account for 10% spare capacity in splitters the true load is actually even a little lower.
58 10% spare capacity means that the OLT will actually serve about 57 users.

3.1.8.4 Interest rate and present values

Discounting of investment and cost positions was conducted by applying the WACC of the steady state model (10% p.a.).

3.1.8.5 Other parameters

All input parameters such as equipment lifetimes, prices etc. have been taken from the steady-state model.

3.2 Our results

3.2.1 Area of profitable coverage and critical market shares

A major set of results of the steady state model consists of the critical market shares required for the viability of the FTTH roll-out for the incumbent and the relevant wholesale access seeker as well. “Market share” always refers to a share of the total potentially addressable market and is in many sections synonymously used with take-up or penetration rate. The “critical market” share is the minimum share of the total potentially addressable market where the operator deploys his network at lower cost per subscriber than the ARPU. The calculation of the critical market share is done separately for each cluster and the results for the clusters are independent from each other. As the maximum achievable market share we assume for fixed lines 70% (taking into account DOCSIS, mobile-only households, and households that do not use telecommunications services at all), a cluster is considered not to be viable if the critical market share for this cluster exceeds this value. It is worth noting that the incumbent may reach the critical market share for viability by his own retail business, by his wholesale business or a combination of both.

The following two tables (Table 3-6 and Table 3-7) show the critical market shares required for deploying P2P and GPON over P2P architectures and the profitability of the corresponding wholesale scenario (fibre unbundling). In case of P2P, the incumbent could profitably roll out up to the suburban cluster or up to 50.7% of the customer base. However, if he deploys a GPON over P2P architecture he could expand his viability up to Cluster 6 and thus cover 64.4% of the addressable subscribers. The viability of this architecture increases up to six percentage points in Cluster 6 compared to P2P primarily due to the smaller number of Ethernet ports required or the port reduction by the OLTs.

Moreover, replicability (another operator building a second NGA identical to the incumbent’s) of the FTTH infrastructure for both technologies is theoretically possible only in the densest cluster or for about 8% of the population. In all other viable areas the investor needs a critical market share of more than 38% to become profitable, which makes the market entry of an infrastructure competitor inefficient.

It is evident from the tables that the first two scenarios are identical wholesale cases. Even though the P2P roll-out requires higher market shares for the incumbent to be viable in total, the network segment rented via unbundled fibre (from the customer's premise to the network sided ODF port) is the same and therefore exhibits equal whole-sale prices in both cases. In both cases we have assumed that the fibre unbundler always implements P2P in his own network. Therefore the first two wholesale scenarios lead to identical results for the competitor.

Table 3-6: P2P Critical market shares

Architecture:	P2P		**Critical market shares**	
Geotype	**Cluster ID**	**Potential customers**	**Incumbent**	**Competitor (LLU)**
Dense urban	1	1,763,916	29%	9%
Urban	2	2,163,672	41%	10%
Less Urban	3	2,646,000	53%	24%
Dense Suburban	4	2,062,480	52%	25%
Suburban	5	2,460,360	67%	> 100%
Less Suburban	6	2,989,056	76%	> 100%
Dense Rural	7	4,331,208	> 100%	> 100%
Rural	8	3,448,368	> 100%	> 100%

Table 3-7: GPON over P2P Critical market shares

Architecture:	GPON over P2P		**Critical market shares**	
Geotype	**Cluster ID**	**Potential customers**	**Incumbent**	**Competitor (LLU)**
Dense urban	1	1,763,916	26%	9%
Urban	2	2,163,672	38%	10%
Less Urban	3	2,646,000	49%	24%
Dense Suburban	4	2,062,480	47%	25%
Suburban	5	2,460,360	61%	> 100%
Less Suburban	6	2,989,056	70%	> 100%
Dense Rural	7	4,331,208	> 100%	> 100%
Rural	8	3,448,368	> 100%	> 100%

Notable here is the huge difference between Cluster 4 and 5 in the wholesale access seeker's profitability. This is caused by the shape of the competitor's cost curve which becomes flat at relatively low take-up rates contrary to the steeper curve of the incumbent. The cost curves per subscriber and month for both incumbent and fibre unbundler with the corresponding ARPU lines are illustrated in the following figures.

Figure 3-1: P2P Cost curves of incumbent and competitors (Cluster 4)

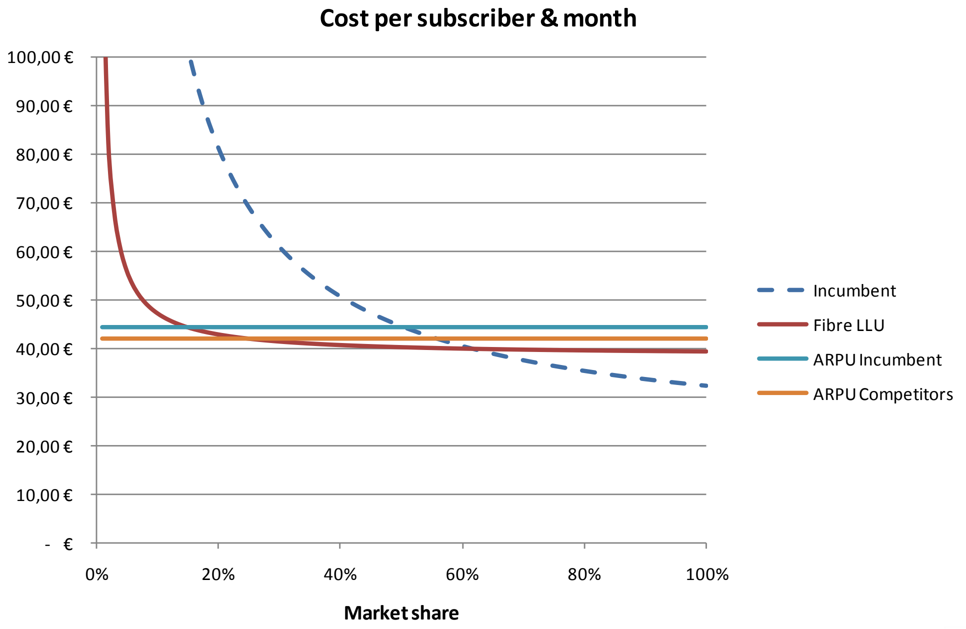


Figure 3-2: P2P Cost curves of incumbent and competitors (Cluster 5)

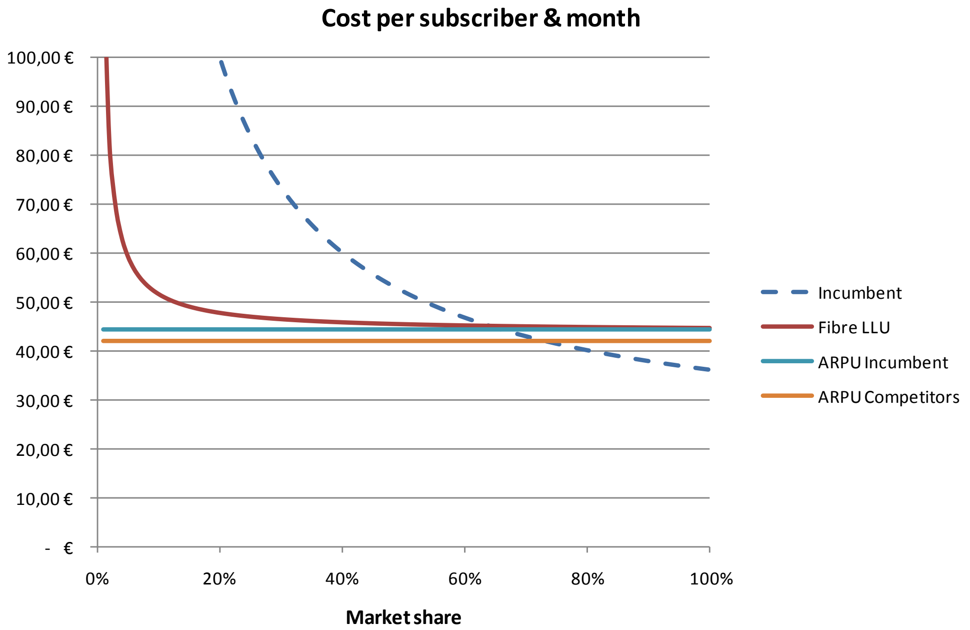


Figure 3-1 shows the cost and revenue curves for Cluster 4 which is the marginal cluster for the competitor. In the next cluster (Figure 3-2) his cost curve is shifted upwards, never going below the ARPU.

The critical market shares for GPON and WDM PON architectures are shown in the next two tables (Table 3-8 and Table 3-9). Except for Cluster 1 the viability potential of rolling out FTTH on the basis of GPON architecture is higher than with WDM PON. Similar to the GPON over P2P technology the incumbent could profitably roll out his network up to the Less Suburban cluster corresponding to 64.4% of the potential customer base. Again, there is no possibility for replication of the FTTH infrastructure except for the densest Cluster 1, since the critical market shares needed for a profitable roll-out in all other viable areas are higher than 38%.

Bitstream access at the core network requires less market share to be profitable than bitstream access at the MPoP level. Furthermore, comparing the three competition scenarios below with the unbundling scenario in Table 3-6, one can state that, for similar ARPUs, business models on the basis of unbundling require higher critical market shares than business models based on bitstream access.[59] For instance, the unbundling scenario already requires a critical market share of 24% in our Less Urban cluster to be profitable, while GPON bitstream access is viable already at 4% / 8% critical market share in the same cluster.

Table 3-8: GPON Critical market shares

Architecture:	GPON		Critical market shares		
Geotype	**Cluster ID**	**Potential customers**	**Incumbent**	**Competitor Bitstream Core**	**Competitor Bitstream MPoP**
Dense urban	1	1,763,916	26%	4%	6%
Urban	2	2,163,672	38%	3%	5%
Less Urban	3	2,646,000	48%	4%	8%
Dense Suburban	4	2,062,480	47%	5%	10%
Suburban	5	2,460,360	60%	16%	28%
Less Suburban	6	2,989,056	69%	> 100%	> 100%
Dense Rural	7	4,331,208	98%	> 100%	> 100%
Rural	8	3,448,368	> 100%	> 100%	> 100%

59 This result goes conform with the Ladder of Investment concept of the ERG, now BEREC.

Table 3-9: WDM PON Critical market shares

Architecture:	WDM PON		Critical market shares	
Geotype	**Cluster ID**	**Potential customers**	**Incumbent**	**Competitor WDM PON Unbundling**
Dense urban	1	1,763,916	25%	4%
Urban	2	2,163,672	39%	3%
Less Urban	3	2,646,000	50%	6%
Dense Suburban	4	2,062,480	49%	6%
Suburban	5	2,460,360	63%	92%
Less Suburban	6	2,989,056	72%	> 100%
Dense Rural	7	4,331,208	> 100%	> 100%
Rural	8	3,448,368	> 100%	> 100%

Another interesting comparison is the one between GPON bitstream core and WDM PON unbundling: As both tables show, the critical market shares of entrants are equal for the first two clusters but the relative profitability of WDM PON unbundling decreases as clusters become less dense. This behaviour is explained by the higher CPE cost for the WDM PON architecture, which overcompensates the savings from the lower wholesale charge (see section 3.2.2.3).

The critical market shares of the different scenarios indicate that in all architectures and wholesale access scenarios considered, potentially several competitors could survive in the market. The highest potential number of competitors occurs in the case of GPON bitstream access at the core network. Critical market shares only provide a theoretical maximum of potential competitors in the market. In particular they do not allow to define an equilibrium between the integrated incumbent and the competitors. The strategic interaction between competitors which also determines the actual number of competitors in the market is produced by our oligopoly model (see chapter 2).

The cost and ARPU curves for the incumbent and the related competitor's scenarios are illustrated in the following figures for GPON (Figure 3-3 and Figure 3-4) and WDM PON (Figure 3-5 and Figure 3-6) showing in each case the last profitable cluster for both operators. Similar to the other two architectures the cost curve of the wholesale scenarios is flatter than the incumbent's one due to lower economies of scale. Thus, the competitor cannot expand his viability to the same cluster as the incumbent.

Figure 3-3: GPON cost curves of incumbent and competitors (Cluster 5)

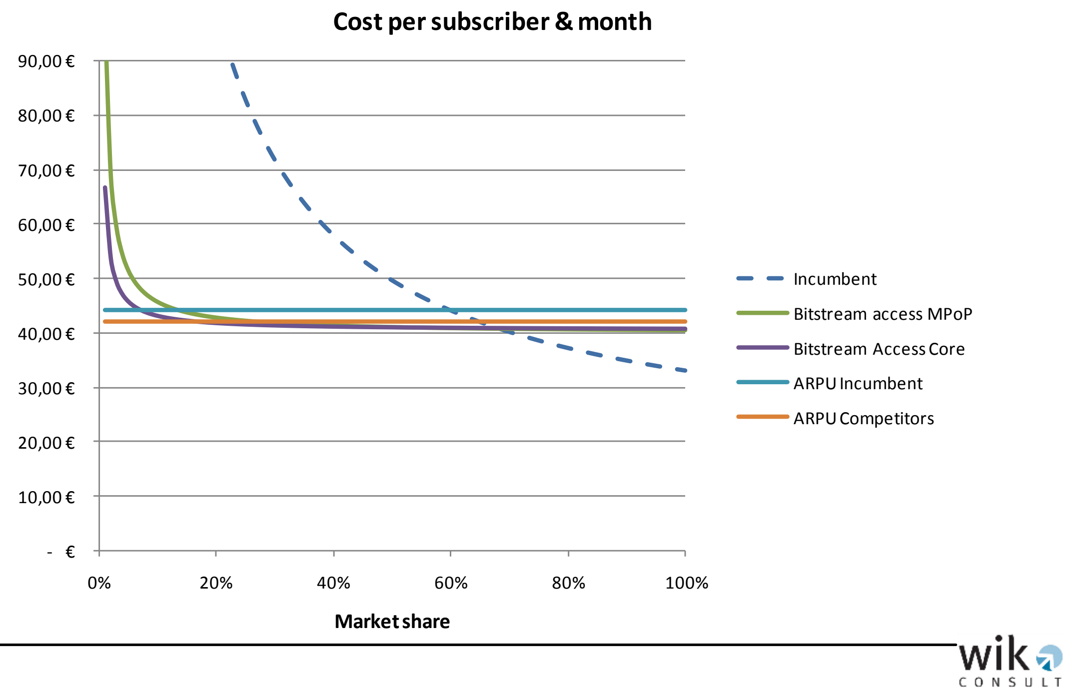


Figure 3-4: GPON Cost curves of incumbent and competitors (Cluster 6)

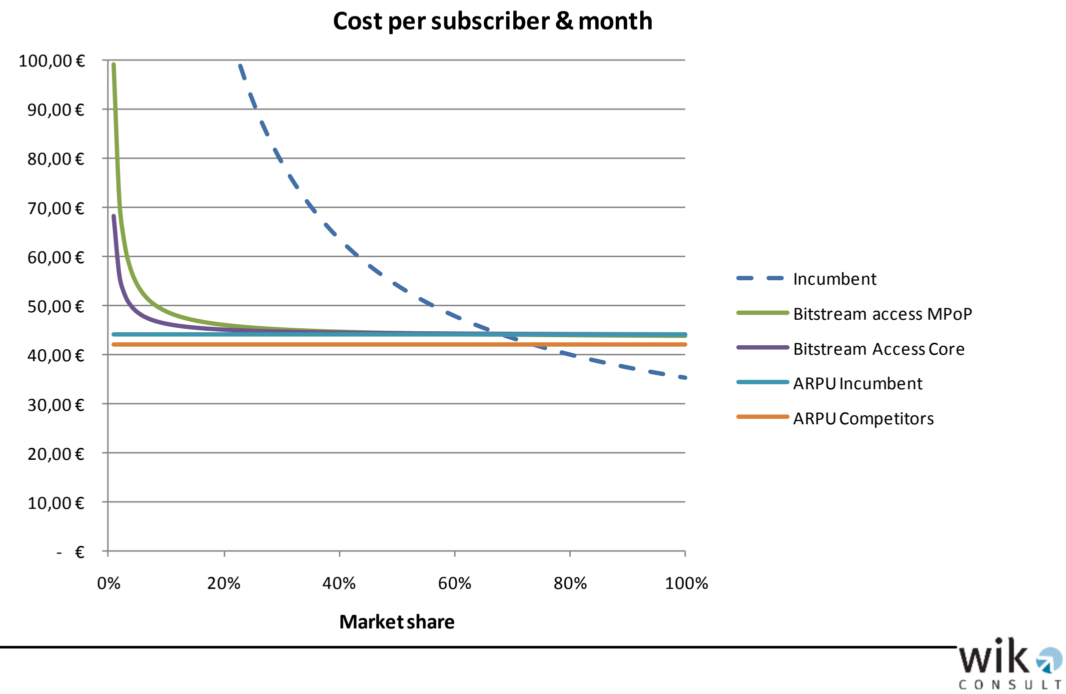


Figure 3-5: WDM PON Cost curves of incumbent and competitors (Cluster 4)

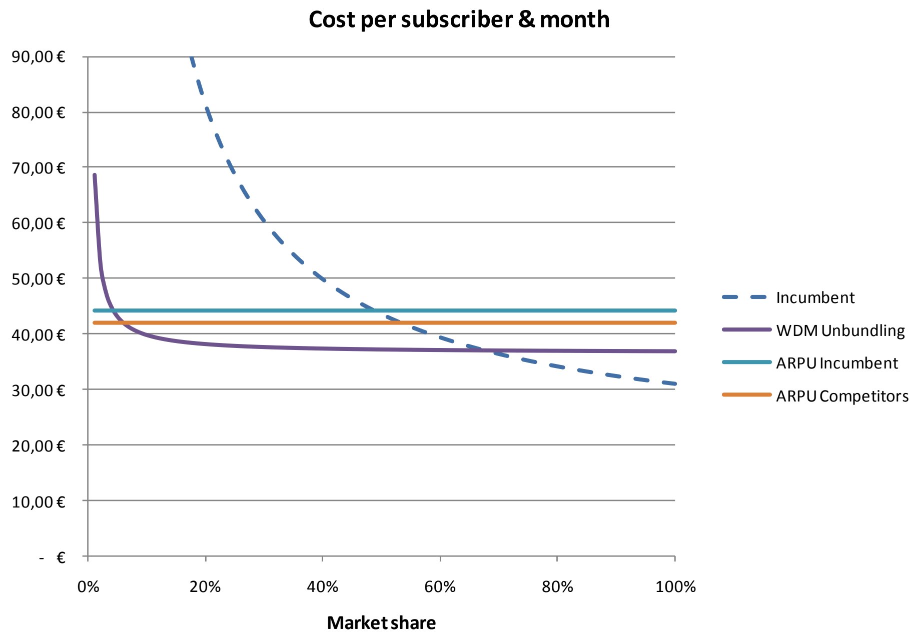
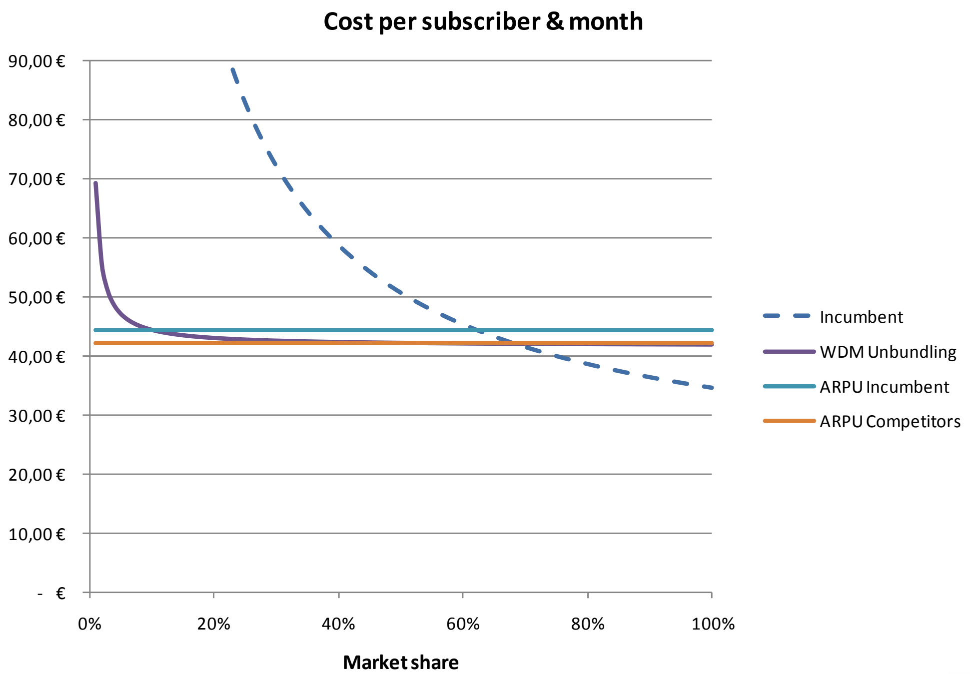


Figure 3-6: WDM PON Cost curves of incumbent and competitors (Cluster 5)



3.2.2 Investment and cost differences of technologies – static approach

3.2.2.1 Investment

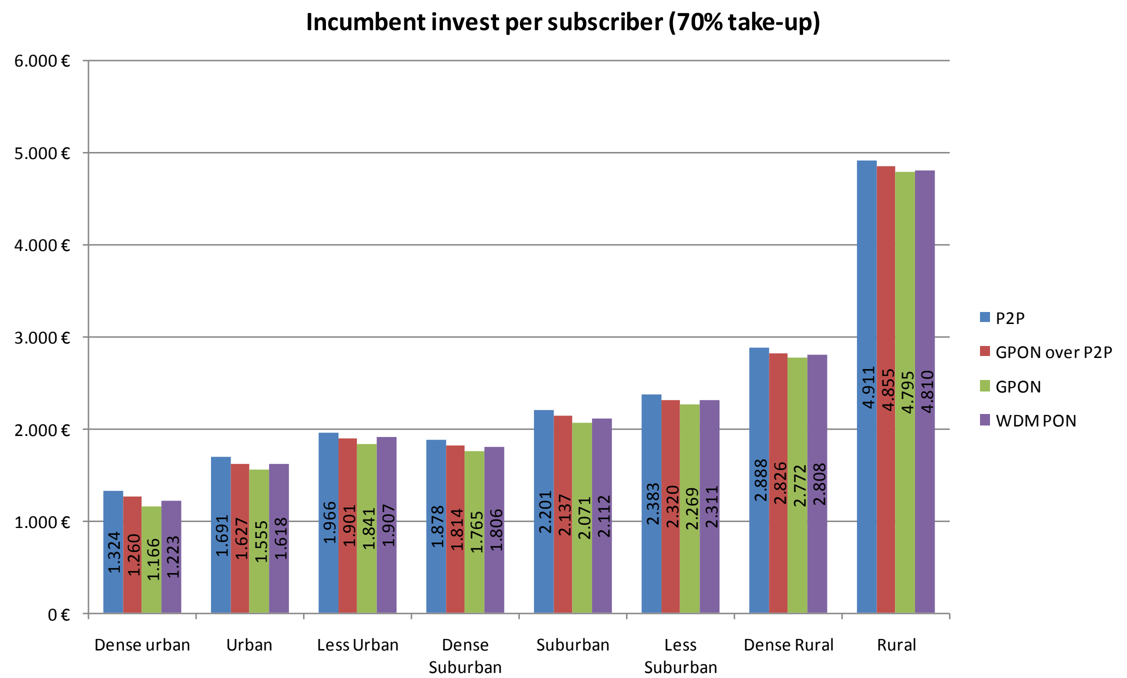
This section analyses investment and its breakdown into access network and MPoP related elements. Table 3-10 shows total investment values for each architecture and cluster at 70% take-up and Figure 3-7 illustrates the corresponding values per subscriber.[60] It is evident that a GPON roll-out requires less investment than all other architectures regardless of the cluster geotype. Except for the third cluster WDM PON shows the second lowest investment and the smallest difference to GPON. As expected P2P is the most investment intensive technology in all clusters. The table also highlights the ranks of the different architectures (1 – lowest investments, 4 – highest investments).

Table 3-10: Total investment per cluster at 70% market share (in Euro, excl. invest in IPTV equipment)

Cluster ID	P2P	GPON over P2P	GPON	WDM PON
1	1,635,366,872 (4)	1,555,206,492 (3)	1,440,199,143 (1)	1,509,953,842 (2)
2	2,561,483,941 (4)	2,463,597,630 (3)	2,355,780,633 (1)	2,450,763,909 (2)
3	3,640,644,636 (4)	3,521,369,571 (2)	3,409,503,170 (1)	3,531,819,963 (3)
4	2,711,585,679 (4)	2,619,329,432 (3)	2,548,335,778 (1)	2,607,106,253 (2)
5	3,790,501,685 (4)	3,680,408,786 (3)	3,566,194,709 (1)	3,638,063,505 (2)
6	4,986,264,055 (4)	4,853,230,188 (3)	4,746,971,414 (1)	4,834,521,602 (2)
7	8,755,484,768 (4)	8,568,721,800 (3)	8,405,447,141 (1)	8,513,102,826 (2)
8	11,854,443,121 (4)	11,718,576,564 (3)	11,574,690,285 (1)	11,609,743,918 (2)
Total	**39,935,774,757 (4)**	**38,980,440,463 (3)**	**38,047,122,274 (1)**	**38,695,075,817 (2)**

60 The values shown in Table 3-10 and throughout this chapter show investments in the NGA up to the MPoP only. For determining the total costs per user and critical market share a national IPTV platform in the core network was also accounted for. The total investments of 15mn € were spread over the clusters.

Figure 3-7: Total investment per subscriber and cluster at 70% market share (excl. invest in IPTV equipment)



In order to better understand the relation between the four architectures and their spread through the different clusters we have classified the investment into access network and MPoP related investments. The following tables (Table 3-11 and Table 3-12) show this breakdown for Cluster 1 and 3 with the corresponding shares of total investment. One can see that the main reason for the advantage of GPON compared to P2P and GPON over P2P consists in the much lower investment in MPoP components due to the use of splitter in the outside plant. Only in case of WDM PON there is less investment in MPoP equipment, however this saving is overcompensated by higher CPE investment due to the increased price per unit. The investment in a standard P2P rollout is always higher than in a GPON over P2P case which is due to the higher number of Ethernet ports required.

Furthermore, it is notable that investment in floorspace exhibits significant differences among the architectures. P2P requires more than two times higher floorspace investment than GPON and even nearly 40 times more than WDM PON in the first cluster. However, these huge differences only have a very limited impact on the overall investment performance of technologies because the investment share of this factor is negligible (< 1%).

Despite of the differences in the implementation of the four technologies, the overall investment deltas between the architectures are relatively small. This follows mainly from the fact that the network elements which are most investment intensive (inhouse cabling and drop cable) and which are identical for all alternatives account for around 75% of total investment, while the feeder segment in which investment savings of e.g. GPON vs. P2P can reach over 100% in the dense areas, has a share of total investment of less than 10% in dense clusters. The difference in feeder investment is not as large as one would initially foresee. The reason is that in this Greenfield deployment civil works have to be undertaken in all cases anyway. Only where the higher fibre count of P2P exceeds the capacity of the standard trench and a wider trench is required does this actually lead to additional civil works cost for P2P. In Euroland this is only the case in the densest Cluster 1. In all other clusters the standard trench has enough capacity to host all required cables. Therefore, from Cluster 2 on the higher fibre count of P2P only leads to additional invest in cables but not to invest in trenches and duct infrastructure. The lower the fibre count becomes as the clusters become less dense, the less pronounced are the differences between P2P and GPON.[61] Therefore, the overall investment deltas between P2P and GPON remain moderate and range from 14% (Cluster 1) to 2% (Cluster 8).

61 A Brownfield sensitivity in section 0 will show how strong the differences between P2P and PON architectures become when taking the feeder fibre count into account for selecting usable duct infrastructure.

Table 3-11: Investment in network elements (Cluster 1)

Cluster 1		Investment in € (70% take-up)							
		P2P	Share of total investment	GPON over P2P	Share of total in-vestment	GPON	Share of total investment	WDM PON	Share of total investment
Access Network									
	CPE	135,204,161	8%	155,484,786	10%	155,484,786	11%	233,227,178	15%
	Inhouse fibre	515,707,301	32%	515,707,301	33%	515,707,301	36%	515,707,301	34%
	Drop cable	632,759,654	39%	632,759,654	41%	632,759,654	44%	632,759,654	42%
	Distribution point	-	0%	-	0%	52,359,615	4%	52,359,615	3%
	Feeder cable	88,415,780	5%	88,415,780	6%	40,111,359	3%	40,111,359	3%
	MDF	-	0%	-	0%	-	0%	4,117,748	0%
	Backhaul cable	-	0%	-	0%	-	0%	11,106,585	1%
	Total	**1,372,086,897 €**	**84%**	**1,392,367,521 €**	**90%**	**1,396,422,715 €**	**97%**	**1,489,389,440 €**	**99%**
MPoP									
	ODF customer sided ports	44,424,224	3%	44,424,224	3%	802,847	0%	66,488	0%
	ODF network sided ports and patch cabling	50,566,356	3%	50,566,356	3%	1,210,554	0%	100,253	0%
	Splitter	-	0%	35,586,405	2%	-	0%	-	0%
	OLT	-	0%	23,724,270	2%	34,906,410	2%	14,454,000	1%
	Ethernet Ports	162,244,994	10%	3,022,200	0%	4,363,301	0%	5,781,600	0%
	"Last Ethernet Port"	151,110	0%	151,110	0%	151,110	0%	8,760	0%
	Floorspace	5,893,290	0%	5,364,405	0%	2,342,205	0%	153,300	0%
	Total	**263,279,975 €**	**16%**	**162,838,971 €**	**10%**	**43,776,428 €**	**3%**	**20,564,401 €**	**1%**
Total invest NGA*)		**1,635,366,872 €**	**100%**	**1,555,206,492 €**	**100%**	**1,440,199,143 €**	**100%**	**1,509,953,842 €**	**100%**

*) Total invest in NGA without investment in IPTV equipment

Table 3-12: Investment in network elements (Cluster 3)

Cluster 3		Investment in € (70% take-up)							
		P2P	Share of total investment	GPON over P2P	Share of total investment	GPON	Share of total investment	WDM PON	Share of total investment
Access Network									
	CPE	202,815,900	6%	233,238,285	7%	233,238,285	7%	349,857,428	10%
	Inhouse fibre	773,597,790	21%	773,597,790	22%	773,597,790	23%	773,597,790	22%
	Drop cable	2,026,707,904	56%	2,026,707,904	58%	2,026,707,904	59%	2,026,707,904	57%
	Distribution point	-	0%	-	0%	86,921,100	3%	86,921,100	2%
	Feeder cable	237,302,426	7%	237,302,426	7%	211,398,839	6%	211,398,839	6%
	MDF	-	0%	-	0%	-	0%	7,588,350	0%
	Backhaul cable	-	0%	-	0%	-	0%	40,728,744	1%
	Total	**3,240,424,020 €**	**89%**	**3,270,846,405 €**	**93%**	**3,331,863,919 €**	**98%**	**3,496,800,155 €**	**99%**
MPoP									
	ODF customer sided ports	66,639,510	2%	66,639,510	2%	1,332,790	0%	113,333	0%
	ODF network sided ports and patch cabling	75,853,147	2%	75,853,147	2%	2,009,616	0%	170,886	0%
	Splitter	-	0%	53,394,390	2%	-	0%	-	0%
	OLT	-	0%	35,596,260	1%	57,947,400	2%	24,637,500	1%
	Ethernet Ports	243,379,080	7%	4,966,920	0%	7,243,425	0%	9,855,000	0%
	"Last Ethernet Port"	551,880	0%	551,880	0%	551,880	0%	13,140	0%
	Floorspace	13,797,000	0%	13,521,060	0%	8,554,140	0%	229,950	0%
	Total	**400,220,617 €**	**11%**	**250,523,167 €**	**7%**	**77,639,251 €**	**2%**	**35,019,808 €**	**1%**
Total invest NGA*)		**3,640,644,636 €**	**100%**	**3,521,369,571 €**	**100%**	**3,409,503,170 €**	**100%**	**3,531,819,963 €**	**100%**

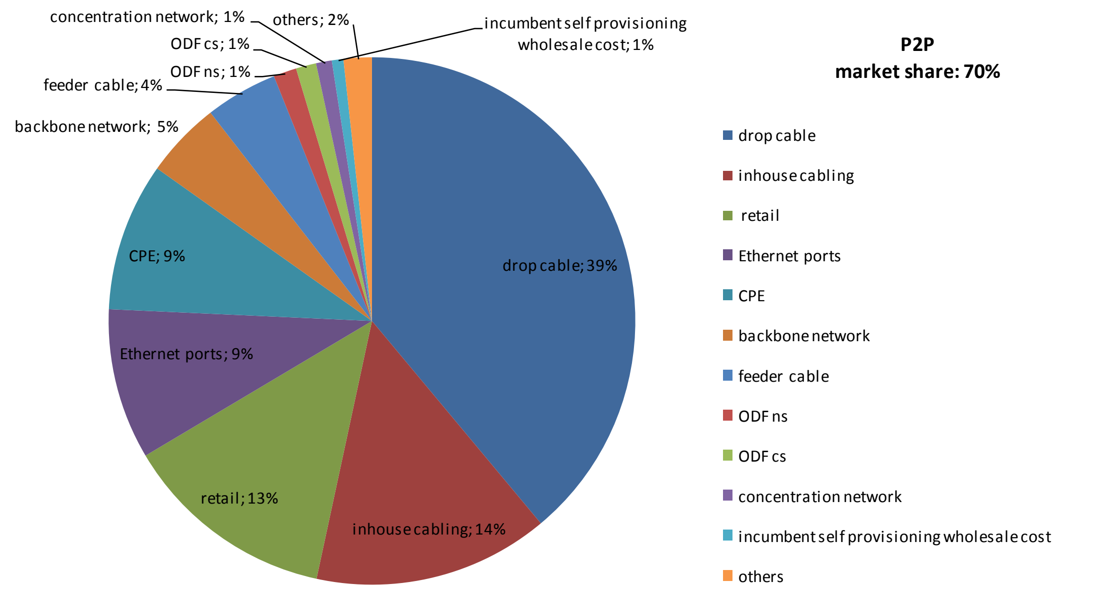
*) Total invest in NGA without investment in IPTV equipment

3.2.2.2 Cost

In the previous section the focus was on the analysis of the *investment* required for the roll-out of a certain technology. We now analyze the *cost* composition of the incumbent and competitors as we consider the annualized cost of NGA investment and direct cost which include floorspace rental, energy, concentration and core network as well as retail costs.

Figure 3-8 up to Figure 3-11 show exemplary for Cluster 3 cost shares of the incumbent's deployment at maximum penetration (70%) for different FTTH architectures. In line with the investment values analysed above, the drop cable segment exhibits the highest cost share regardless of the technology deployed (between 39% and 42%). The second largest cost component is the inhouse cabling (14%-16%), except for WDM PON case where the cost for CPE dominates with 16% cost share due to the higher equipment price assumed.[62] Retail cost ranges between 13% and 15% along the different architectures, CPE cost – between 9% and 11% (except for WDM PON). As expected, the costs of Ethernet ports have a significant impact only in case of P2P where it generates 9% of the total cost. Contrary to this, the PON architectures' cost of active equipment (OLTs and PON Ethernet ports) in the MPoP account for a maximum of 2% of the total cost.

Figure 3-8: P2P Cost structure of incumbent at 70% market share (Cluster 3)



62 We will show a sensitivity on CPE prices in section 0.

Figure 3-9: GPON over P2P Cost structure of incumbent at 70% market share (Cluster 3)

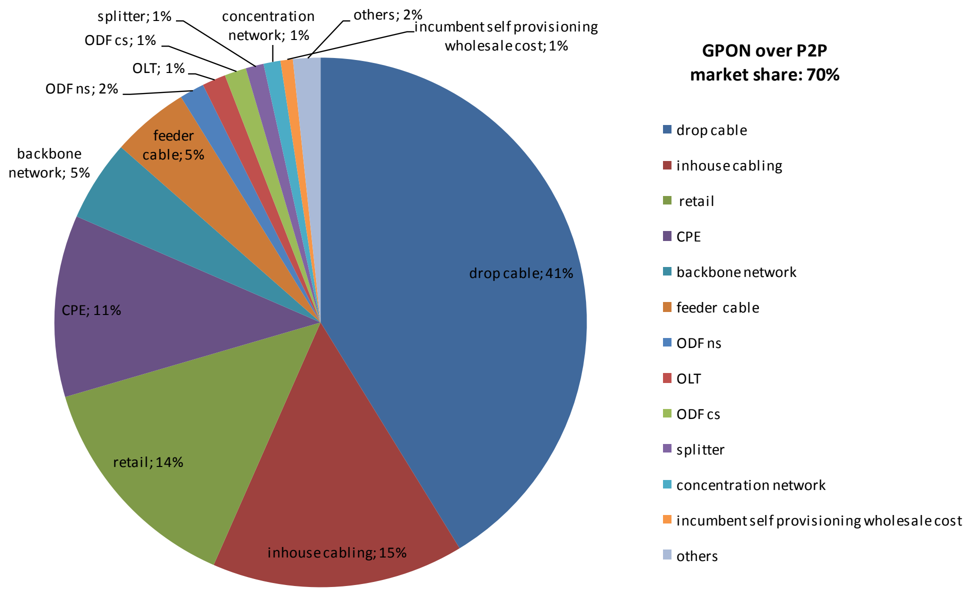


Figure 3-10: GPON Cost structure of incumbent at 70% market share (Cluster 3)

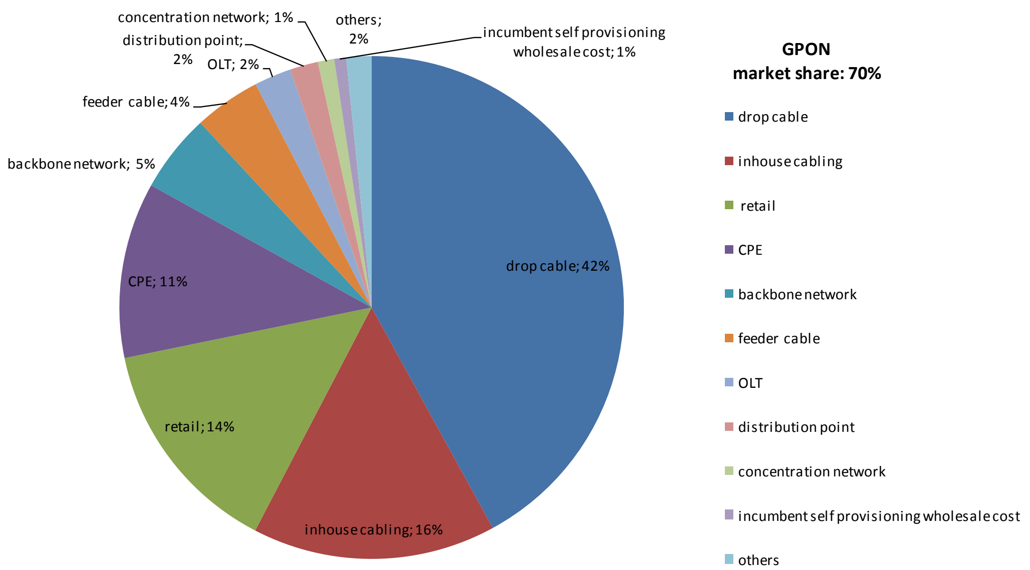
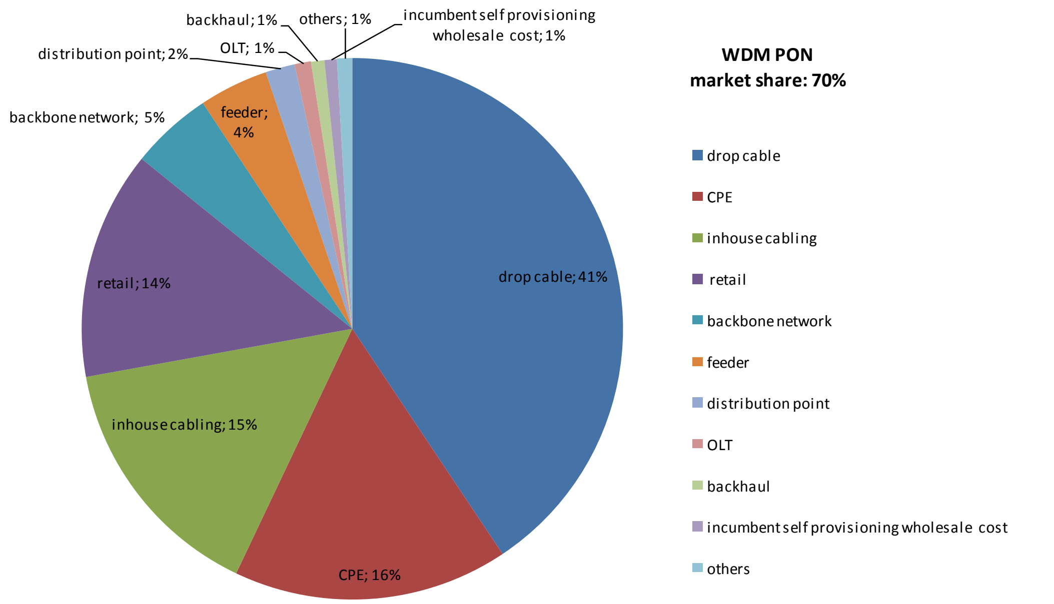


Figure 3-11: WDM PON cost structure of incumbent at 70% market share (Cluster 3)



In the relevant clusters 1-6 the cost comparison of our four network topologies has shown the following results: GPON is the cheapest technology, followed by GPON over P2P, WDM PON and P2P (see Table 3-13). With the exception of Cluster 1 where WDM PON and GPON over P2P switch ranks, this is consistent over the relevant clusters.

Table 3-13: Total cost per customer per month at 70% take-up (in Euro)

Cluster	P2P	GPON over P2P	GPON	WDM PON
1	29.85	27.67	26.55	27.49
2	34.17	32.00	31.18	32.42
3	38.19	36.03	35.37	36.62
4	37.73	35.58	35.04	36.33
5	43.02	40.87	40.14	41.50
6	46.21	44.07	43.50	44.83

The next four figures depict the cost composition of a competitor for the five wholesale scenarios and at 20% market share (examples shown for Cluster 3). One can see that the cost structure of a competitor in a FTTH network is strongly dominated by the wholesale price. In the bitstream scenarios the cost share of the wholesale price amounts to 65% on average. The cost share of the wholesale provision will be reduced to 57% in case of fibre unbundling.

Figure 3-12: Cost structure of fibre unbundler at 20% market share (Cluster 3)

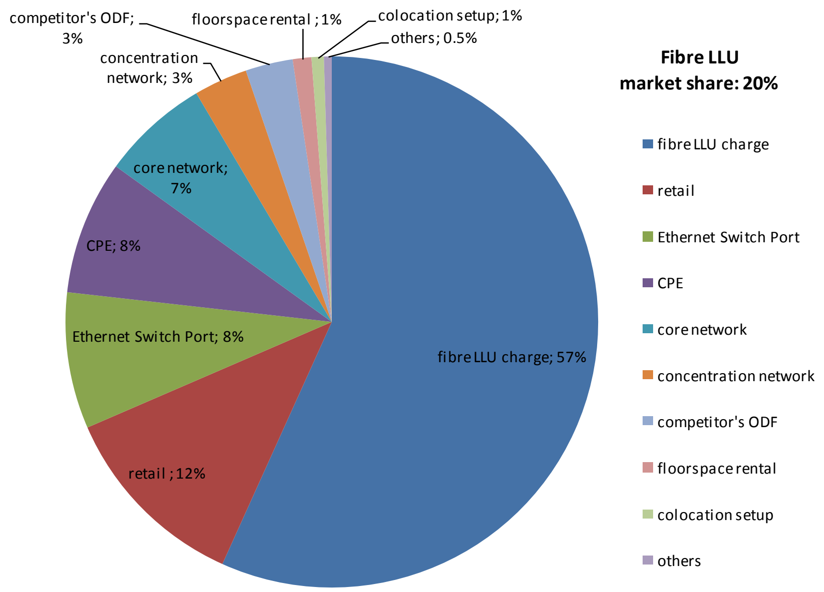


Figure 3-13: Cost structure of a bitstream MPoP access seeker at 20% market share (Cluster 3)

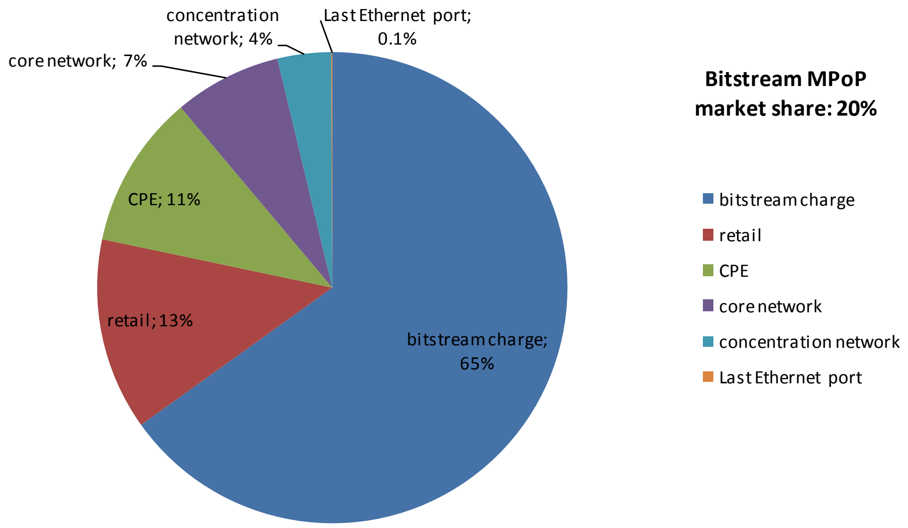


Figure 3-14: Cost structure of a bitstream core access seeker (GPON) at 20% market share (Cluster 3)

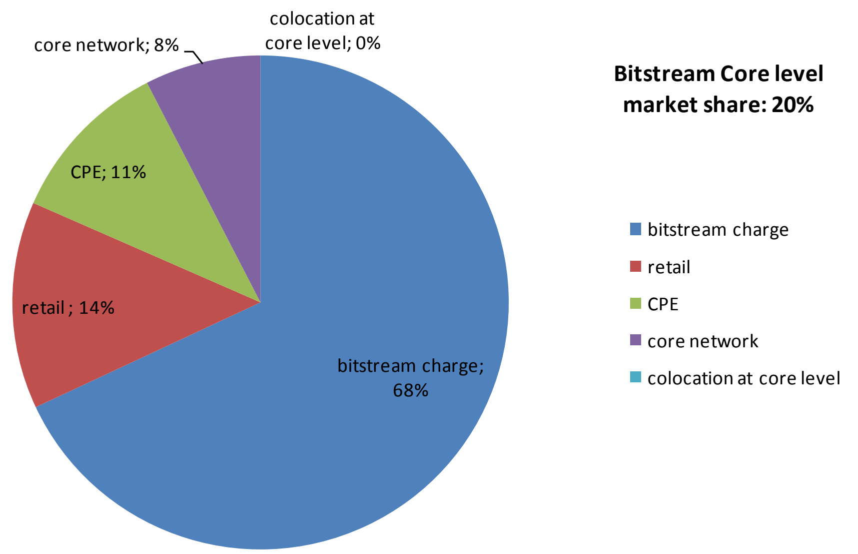
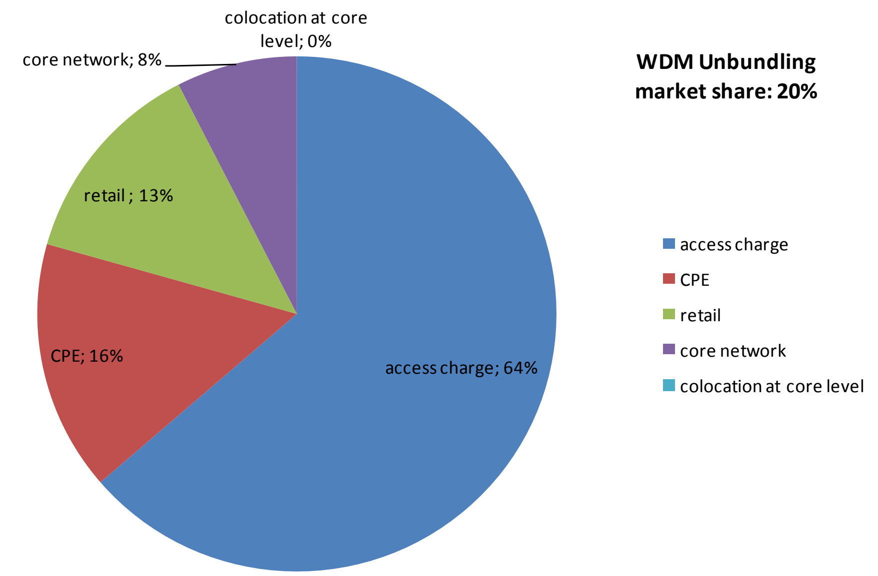


Figure 3-15: Cost structure of a WDM unbundler at 20% market share (Cluster 3)



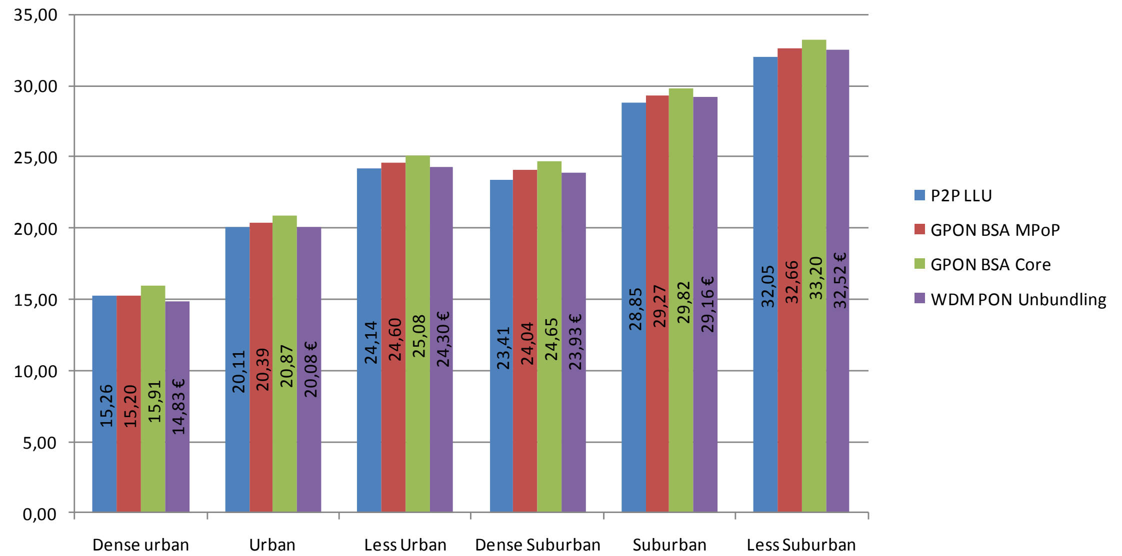
3.2.2.3 Wholesale prices

As explained before, wholesale prices for the competitor's business case have been determined based on the LRIC incurred for the incumbent at a 70% take-up which is the maximum penetration rate we assume for the incumbent's network. Depending on the scenario they can - in addition to the cost of the access network (which includes the optical inhouse cabling cost) – include cost for active equipment in the MPoP or cost for transport in concentration/the backhaul network.

Figure 3-16 provides an overview of the resulting wholesale prices. In line with the components included in the wholesale charge, bitstream access at the core level is more expensive than access at the MPoP or WDM unbundling along all clusters. Note that a comparison between the fibre unbundling charge and the wholesale prices of the other competition scenarios is not directly possible, since they are based on different access technologies according to the scenario definition. Accordingly the most valid interpretation is the comparison of the two GPON bitstream scenarios. The wholesale price increase for the bitstream access at the core level is relatively small. The reason is that the concentration network transport component of the access charge at the core level is based upon a 70% network load which results in very low transport cost per customer, considering that the dominant part of the concentration network costs is fix.

Furthermore, it is interesting to note that in some clusters the WDM PON access charge is below the GPON access charge level, but as we have seen GPON always leads in terms of overall cost and thus critical market shares. The reason is primarily the CPE price that is borne by every subscriber. We have run a sensitivity on the WDM PON CPE price and other parameters in the next section.

Figure 3-16: Wholesale prices



3.2.2.4 Sensitivities: Impact on critical market shares

Investment reduction for the incumbent ("Brownfield deployment")

In bottom up LRIC modelling we consider the situation that an investor constructs a new, state of the art forward looking fibre network, taking into account future demand (Greenfield scenario).

In the real world the investors often face the situation that locations and infrastructure already exist which may be reused by a new network generation in order to save investment. This will be considered in our modelling approach by taking the existing MDF locations as scorched nodes of the new network (maybe some of the MDF will be dismantled), not looking for new locations, thus the remaining are a subset of the existing. Regardless of any dismantling scenarios, the cost of the locations that are in use are fully considered.

The investor's decision nevertheless is driven by the level of (additional) investments he has to make, considering that there are existing ducts having spare capacity which could satisfy part of the demand of the new network, thus resulting in less investment expenditures. We face that situation by defining a scenario which we call Brownfield in contrast to the above mentioned Greenfield scenario, where we reduce the investment for the passive network components ducts, trenches and manholes[63] by dedicated per-

63 For ease of expression in this section we call these components „duct infrastructure" only, since the ducts determine their ability to be reused. Direct buried lines could not be reused.

centages due to the NGA architecture and their fibre demand and due to the part (segment) of the access network, where this spare capacity is located. This Brownfield scenario is part of the sensitivities we consider in all our models.

Proceeding like this requires that duct infrastructure exists which still has spare capacity in an amount being able to host all of the new required fibre cables. If only part of the cables could be hosted, a new trench has to be dug anyhow, so no significant savings would be achieved.

Our basic assumption is that on average the spare components have existed for half of the total equipment life time, thus we assume that the new FTTH network can use the duct infrastructure of an older network for an average remaining lifetime. In the cases where the existing infrastructure has been reinvested in the shorter term future (e.g. due to poor constitution of the ducts) an investor may decide to reinvest now before the new fibre cables will be plugged in. Otherwise reinvestment can hardly be managed without broadband customer interruption (relatively soon after they have taken up the service). In consequence for the components being reused we only consider half of the investment one would need in a Greenfield environment. E.g. we assume the few fibres in the backhaul segment of the highly aggregated WDM PON architecture will fit into the already existing ducts of the old concentration network by 100%. Due to the already used ducts and the sooner reinvestment we for simplicity assume that 50% of the investment may be saved, thus we reduce the investment for the trenches, ducts and manholes of the backhaul segment by 50%. We also did an additional sensitivity to consider that all ducts may still be usable for more than the fibre equipment lifetime considered (20 years).

In the feeder network segment the fibre plants of GPON and WDM PON are equal, and the fibre plants for P2P and GPON over P2P are also equal, requiring one fibre per home passed. Accordingly, P2P plants have 64 times more fibres than the PON plants. Therefore, we assume in our Brownfield scenarios that for the first two architectures (GPON and WDM PON) all feeder fibres fit into already existing ducts, thus reducing the necessary investment for the feeder duct infrastructure by 50% at the maximum. For the second two architectures, needing significantly more fibres, we assume that only in 20% of the cases the existing duct network may also host the new fibre cables, resulting in an investment reduction of 10% of the feeder duct infrastructure. We believe these assumptions to be optimistic, since we assume here that in Euroland all feeder cables are already constructed in a ducted manner.

In the drop network, the fibre plants of all network architectures are equal, all having one fibre from the home passed to the distribution point (DP). In this network segment sharing of existing ducts only can take place where ducts are deployed. For our Brownfield scenario we assume optimistically that ducts exist in half of the areas where there is no aerial construction[64] and that all of these ducts can be shared with the new fibre cables. For the ducts to be installed these assumptions reduce the required investment for duct infrastructure by 25% in the drop cable segment. The resulting investment reductions are given in Table 3-14.

The Brownfield scenario in this study considers the reduced investment for the calculation of the incumbent's profitability. The comparison with the wholesale based competitors still assumes the Greenfield LRIC based wholesale prices as an input, since price regulation in all European countries operates accordingly. An additional sensitivity analyses the results if this assumption of existing regulatory practice would no longer hold and wholesale prices also reflected the investment savings of the Brownfield approach.

Table 3-14: Investment reduction for duct infrastructure per network segment in a Brownfield approach

Network Segment	P2P	GPON over P2P	GPON	WDM PON
Backhaul	--	--	--	50%
Feeder	10%	10%	50%	50%
Drop	25%	25%	25%	25%

Table 3-15 compares the resulting critical market shares for Greenfield and brownfield scenarios. Lower investment requirements in a brownfield approach enable the incumbent to increase the profitable coverage with P2P and WDM PON up to the Less Suburban Cluster 6. For all technologies costs and critical market shares decrease. The strongest effects occur for the WDM PON architecture. As Table 3-17 shows, total network costs here decrease from 5% (Cluster 1) to 11% (Cluster 8). The lowest cost savings occur with P2P from 4% (Cluster 1) to 7% (Cluster 3). Cost savings for GPON are higher than for P2P but slightly lower than for WDM PON, and range from 5% (Cluster 1) to 10% (Cluster 8).

The investment savings become more transparent by segment (see Table 3-16). The effective reduction in the drop segment ranges from 7% to 20% depending on the cluster and is similar for all architectures, as one could expect with the same fibre plant in all architecture variants. In the feeder segment, the savings for P2P are around 7% and for GPON around 40%. The savings in the backhaul segment amount to around 40% for WDM PON in the relevant cluster. In terms of total cost, investment savings reduce costs by 5% to 10% for GPON and 4% to 7% for P2P.

64 For aerial deployment shares see Table 3-2.

Table 3-15: Incumbent critical market shares (Greenfield vs. Brownfield)

Cluster ID	P2P - Greenfield	P2P - Brownfield	GPON over P2P - Greenfield	GPON over P2P - Brownfield	GPON - Greenfield	GPON - Brownfield	WDM PON - Greenfield	WDM PON - Brownfield
1	29%	25%	26%	23%	26%	23%	25%	22%
2	41%	34%	38%	32%	38%	31%	39%	31%
3	53%	45%	49%	41%	48%	40%	50%	41%
4	52%	45%	47%	41%	47%	40%	49%	41%
5	67%	60%	61%	55%	60%	52%	63%	54%
6	76%	68%	70%	63%	69%	59%	72%	62%
7	> 100%	> 100%	> 100%	95%	98%	86%	> 100%	89%
8	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%

Table 3-16: Incumbent investment at 70% market share

Cluster ID		P2P - greenfield	P2P - brownfield	Effective reduction of invest	GPON over P2P - greenfield	GPON over P2P - brownfield	Effective reduction of invest	GPON -greenfield	GPON - brownfield	Effective reduction of invest	WDM PON - greenfield	WDM PON - brownfield	Effective reduction of invest
1	**Total Investment**	**1.635.576.824**	**1.526.031.309**	**7%**	**1.555.416.445**	**1.445.870.929**	**7%**	**1.440.409.096**	**1.319.372.425**	**8%**	**1.511.413.842**	**1.385.957.204**	**8%**
	Drop	632.759.654	527.251.572	17%	632.759.654	527.251.572	17%	632.759.654	527.251.572	17%	632.759.654	527.251.572	17%
	Feeder	88.415.780	84.378.347	5%	88.415.780	84.378.347	5%	40.111.359	24.582.771	39%	40.111.359	24.582.771	39%
	Backhaul	-	-		-	-		-	-		11.106.585	6.686.618	40%
2	**Total Investment**	**2.561.995.131**	**2.294.654.186**	**10%**	**2.464.108.819**	**2.196.767.875**	**11%**	**2.356.291.823**	**2.056.035.267**	**13%**	**2.452.588.909**	**2.142.766.434**	**13%**
	Drop	1.298.246.556	1.039.134.514	20%	1.298.246.556	1.039.134.514	20%	1.298.246.556	1.039.134.514	20%	1.298.246.556	1.039.134.514	20%
	Feeder	138.607.451	130.378.548	6%	138.607.451	130.378.548	6%	108.237.243	67.092.729	38%	108.237.243	67.092.729	38%
	Backhaul	-	-		-	-		-	-		24.650.640	15.084.720	39%
3	**Total Investment**	**3.641.411.420**	**3.246.547.120**	**11%**	**3.522.136.355**	**3.127.272.055**	**11%**	**3.410.269.954**	**2.948.775.039**	**14%**	**3.534.009.963**	**3.056.289.777**	**14%**
	Drop	2.026.707.904	1.648.501.257	19%	2.026.707.904	1.648.501.257	19%	2.026.707.904	1.648.501.257	19%	2.026.707.904	1.648.501.257	19%
	Feeder	237.302.426	220.644.772	7%	237.302.426	220.644.772	7%	211.398.839	128.110.572	39%	211.398.839	128.110.572	39%
	Backhaul	-	-		-	-		-	-		40.728.744	24.503.472	40%
4	**Total Investment**	**2.712.437.661**	**2.461.888.717**	**9%**	**2.620.181.415**	**2.369.632.471**	**10%**	**2.549.187.760**	**2.221.175.028**	**13%**	**2.608.566.253**	**2.280.553.521**	**13%**
	Drop	1.385.532.510	1.154.349.513	17%	1.385.532.510	1.154.349.513	17%	1.385.532.510	1.154.349.513	17%	1.385.532.510	1.154.349.513	17%
	Feeder	250.087.722	230.721.775	8%	250.087.722	230.721.775	8%	248.622.143	151.792.407	39%	248.622.143	151.792.407	39%
	Backhaul	-	-		-	-		-	-		-	-	
5	**Total Investment**	**3.791.423.651**	**3.484.147.716**	**8%**	**3.681.330.753**	**3.374.054.817**	**8%**	**3.567.116.676**	**3.150.343.720**	**12%**	**3.639.888.505**	**3.223.115.549**	**11%**
	Drop	2.124.752.586	1.844.850.905	13%	2.124.752.586	1.844.850.905	13%	2.124.752.586	1.844.850.905	13%	2.124.752.586	1.844.850.905	13%
	Feeder	383.114.208	355.739.953	7%	383.114.208	355.739.953	7%	344.763.223	207.891.948	40%	344.763.223	207.891.948	40%
	Backhaul	-	-		-	-		-	-		-	-	
6	**Total Investment**	**4.987.532.900**	**4.600.961.461**	**8%**	**4.854.499.033**	**4.467.927.594**	**8%**	**4.748.240.259**	**4.169.922.776**	**12%**	**4.836.711.602**	**4.258.394.119**	**12%**
	Drop	2.819.303.502	2.480.668.573	12%	2.819.303.502	2.480.668.573	12%	2.819.303.502	2.480.668.573	12%	2.819.303.502	2.480.668.573	12%
	Feeder	607.049.450	559.112.940	8%	607.049.450	559.112.940	8%	603.733.176	364.050.622	40%	603.733.176	364.050.622	40%
	Backhaul	-	-		-	-		-	-		-	-	
7	**Total Investment**	**8.759.808.578**	**8.279.150.607**	**5%**	**8.573.045.610**	**8.092.387.639**	**6%**	**8.409.770.951**	**7.426.234.268**	**12%**	**8.516.022.826**	**7.532.486.142**	**12%**
	Drop	4.907.022.551	4.552.084.259	7%	4.907.022.551	4.552.084.259	7%	4.907.022.551	4.552.084.259	7%	4.907.022.551	4.552.084.259	7%
	Feeder	1.556.312.538	1.430.592.860	8%	1.556.312.538	1.430.592.860	8%	1.548.543.771	919.945.380	41%	1.548.543.771	919.945.380	41%
	Backhaul	-	-		-	-		-	-		-	-	
8	**Total Investment**	**11.862.013.592**	**11.118.086.847**	**6%**	**11.726.147.034**	**10.982.220.289**	**6%**	**11.582.260.756**	**9.997.802.281**	**14%**	**11.612.298.918**	**10.027.840.443**	**14%**
	Drop	7.379.700.453	6.845.906.641	7%	7.379.700.453	6.845.906.641	7%	7.379.700.453	6.845.906.641	7%	7.379.700.453	6.845.906.641	7%
	Feeder	2.601.283.443	2.391.150.511	8%	2.601.283.443	2.391.150.511	8%	2.588.298.413	1.537.633.751	41%	2.588.298.413	1.537.633.751	41%
	Backhaul	-	-		-	-		-	-		-	-	

Table 3-17: Incumbent total cost per subscriber and month at 70% market share

Cluster ID		P2P - greenfield	P2P - brownfield	Effective reduction of cost	GPON over P2P - greenfield	GPON over P2P - brownfield	Effective reduction of cost	GPON -greenfield	GPON - brownfield	Effective reduction of cost	WDM PON - greenfield	WDM PON - brownfield	Effective reduction of cost
1	**Total Cost**	**29,85**	**28,68**	**4%**	**27,67**	**26,50**	**4%**	**26,55**	**25,25**	**5%**	**27,49**	**26,15**	**5%**
	Drop	6,77	5,64	17%	6,77	5,64	17%	6,77	5,64	17%	6,77	5,64	17%
	Feeder	0,95	0,90	5%	0,95	0,90	5%	0,43	0,26	39%	0,43	0,26	39%
	Backhaul	-	-		-	-		-	-		0,12	0,07	40%
2	**Total Cost**	**34,17**	**31,84**	**7%**	**32,00**	**29,67**	**7%**	**31,18**	**28,56**	**8%**	**32,42**	**29,71**	**8%**
	Drop	11,33	9,07	20%	11,33	9,07	20%	11,33	9,07	20%	11,33	9,07	20%
	Feeder	1,21	1,14	6%	1,21	1,14	6%	0,94	0,59	38%	0,94	0,59	38%
	Backhaul	-	-		-	-		-	-		0,22	0,13	39%
3	**Total Cost**	**38,19**	**35,33**	**7%**	**36,03**	**33,17**	**8%**	**35,37**	**32,04**	**9%**	**36,62**	**33,17**	**9%**
	Drop	14,86	12,13	18%	14,86	12,13	18%	14,86	12,13	18%	14,86	12,13	18%
	Feeder	1,69	1,57	7%	1,69	1,57	7%	1,51	0,91	39%	1,51	0,91	39%
	Backhaul	-	-		-	-		-	-		0,29	0,17	40%
4	**Total Cost**	**37,73**	**35,35**	**6%**	**35,58**	**33,20**	**7%**	**35,04**	**31,96**	**9%**	**36,33**	**33,25**	**8%**
	Drop	13,51	11,31	16%	13,51	11,31	16%	13,51	11,31	16%	13,51	11,31	16%
	Feeder	2,29	2,11	8%	2,29	2,11	8%	2,28	1,39	39%	2,28	1,39	39%
	Backhaul	-	-		-	-		-	-		-	-	
5	**Total Cost**	**43,02**	**40,52**	**6%**	**40,87**	**38,38**	**6%**	**40,14**	**36,80**	**8%**	**41,50**	**38,16**	**8%**
	Drop	18,30	16,01	13%	18,30	16,01	13%	18,30	16,01	13%	18,30	16,01	13%
	Feeder	2,94	2,73	7%	2,94	2,73	7%	2,65	1,60	40%	2,65	1,60	40%
	Backhaul	-	-		-	-		-	-		-	-	
6	**Total Cost**	**46,21**	**43,56**	**6%**	**44,07**	**41,42**	**6%**	**43,50**	**39,63**	**9%**	**44,83**	**40,96**	**9%**
	Drop	20,59	18,25	11%	20,59	18,25	11%	20,59	18,25	11%	20,59	18,25	11%
	Feeder	3,83	3,53	8%	3,83	3,53	8%	3,81	2,30	40%	3,81	2,30	40%
	Backhaul	-	-		-	-		-	-		-	-	
7	**Total Cost**	**57,77**	**55,33**	**4%**	**55,69**	**53,25**	**4%**	**54,97**	**50,34**	**8%**	**55,68**	**51,04**	**8%**
	Drop	28,36	26,46	7%	28,36	26,46	7%	28,36	26,46	7%	28,36	26,46	7%
	Feeder	6,79	6,24	8%	6,79	6,24	8%	6,75	4,01	41%	6,75	4,01	41%
	Backhaul	-	-		-	-		-	-		-	-	
8	**Total Cost**	**92,44**	**87,71**	**5%**	**90,50**	**85,77**	**5%**	**89,53**	**80,20**	**10%**	**88,82**	**79,48**	**11%**
	Drop	53,56	49,98	7%	53,56	49,98	7%	53,56	49,98	7%	53,56	49,98	7%
	Feeder	14,24	13,09	8%	14,24	13,09	8%	14,17	8,42	41%	14,17	8,42	41%
	Backhaul	-	-		-	-		-	-		-	-	

We now assume that the wholesale prices are based on the incumbent's brownfield costs (and no longer on the Greenfield LRIC) and analyse the impact on the competition scenarios. As expected, wholesale access seekers improve their viability compared to a Greenfield environment, as Table 3-18 shows. All bitstream access seekers can expand their profitable coverage at least by one cluster. The limit of viability for the fibre unbundler remains in Cluster 4 but the critical market share decreases significantly in this marginal cluster (from 25% to 15%).

Table 3-18: Competitors critical market shares (Greenfield vs. Brownfield)

Cluster ID	LLU - Greenfield	LLU - Brownfield	Bitstream Core - Greenfield	Bitstream Core - Brownfield	Bitstream MPoP - Greenfield	Bitstream MPoP - Brownfield	WDM un-bundling - Greenfield	WDM un-bundling - Brownfield
1	9%	8%	4%	3%	6%	6%	4%	4%
2	10%	8%	3%	2%	5%	4%	3%	3%
3	24%	12%	4%	3%	8%	6%	6%	4%
4	25%	15%	5%	4%	10%	7%	6%	4%
5	> 100%	> 100%	16%	6%	28%	11%	92%	8%
6	> 100%	> 100%	> 100%	12%	> 100%	22%	> 100%	32%
7	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
8	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%

So far, we have assumed that only (up to) 50% of the investment (where possible) may be saved due to the already used ducts and the sooner reinvestment required. We now run an additional sensitivity assuming a full duct lifetime of existing infrastructure. The resulting investment reductions are shown in Table 3-19. For all network segments we now consider twice as much savings as in the standard brownfield scenario. This means that in case of GPON and WDM PON the incumbent can even save the entire duct infrastructure investment in feeder and backhaul segment as all fibres fit into already existing ducts.

Table 3-19: Investment reduction for duct infrastructure per network segment in a Brownfield approach when considering full duct lifetime

Network Segment	P2P	GPON over P2P	GPON	WDM PON
Backhaul	--	--	--	100%
Feeder	20%	20%	100%	100%
Drop	50%	50%	50%	50%

Such drastic savings result in lower critical market shares for both incumbent (Table 3-20) and competitor (Table 3-21). The strongest impact occurs for GPON and WDM PON due to the higher reduction in feeder and backhaul (relevant only for WDM PON) segment. Nevertheless, the incumbent is not able to expand his profitable coverage compared to the previous calculation as the limit of profitable roll-out remains in the Less Suburban Cluster 6 for all architectures. This also holds for the competition scenarios except for the fibre unbundler, who can expand his viability one cluster further.

Table 3-20: Impact of assuming full duct lifetime on incumbent's Brownfield viability

Cluster ID	P2P - Brownfield	P2P - Brownfield sensitivity	GPON over P2P - Brownfield	GPON over P2P - Brown-field sensi-tivity	GPON - Brownfield	GPON - Brownfield sensitivity	WDM PON - Brownfield	WDM PON - Brownfield sensitivity
1	25%	22%	23%	20%	23%	19%	22%	18%
2	34%	28%	32%	25%	31%	24%	31%	24%
3	45%	36%	41%	33%	40%	31%	41%	31%
4	45%	38%	41%	35%	40%	32%	41%	32%
5	60%	52%	55%	48%	52%	43%	54%	45%
6	68%	61%	63%	56%	59%	49%	62%	51%
7	> 100%	96%	95%	88%	86%	74%	89%	76%
8	> 100%	>100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%

Table 3-21: Impact of assuming full duct lifetime on competitor's Brownfield viability

Cluster ID	LLU - brownfield	LLU - brownfield sensitivity	Bitstream Core - brownfield	Bitstream Core - brownfield sensitivity	Bitstream MPoP - brownfield	Bitstream MPoP - brownfield sensitivity	WDM un-bundling - brownfield	WDM un-bundling - brownfield sensitivity
1	8%	8%	3%	3%	6%	5%	4%	3%
2	8%	6%	2%	2%	4%	4%	3%	2%
3	12%	8%	3%	2%	6%	4%	4%	3%
4	15%	11%	4%	3%	7%	5%	4%	3%
5	> 100%	25%	6%	4%	11%	7%	8%	4%
6	> 100%	> 100%	12%	5%	22%	9%	32%	6%
7	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
8	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%

Lower NGA penetration

Even though a 70% maximum take-up on a next generation fibre-based fixed network that has replaced copper appears realistic to us we have conducted a sensitivity analysis for which we assume a maximum take-up of only 60%. On the modelling side the only changes for the incumbent are that he will plan his MPoP floorspace for 60% instead of 70% take-up. This reduction of floorspace cost, however, does not have impacts on his critical market shares in any of the clusters. Accordingly, one can simply analyse Table 3-6 to Table 3-9 and draw the limit of viable roll-out at 60% for the incumbent. This reduces the viable reach by one cluster for all architectures except for GPON over P2P where the incumbent loses 2 clusters.

Since the wholesale price was determined on the basis of the maximum take-up rate, the impact on the competitor cases is much more significant as they have to cope with an increase of the wholesale price. Not only do competitors lose viable coverage for one cluster in bitstream cases and two clusters in the fibre LLU case, they also experience significant increases in critical market shares in some clusters that remain viable. Only in case of WDM unbundling the limit of profitable roll-out remains the same as in the base case, the critical market share, however, increases from 6% to 13% in the last profitable cluster.

Table 3-22: Competitors' critical market shares (70% vs. 60% incumbent maximum take-up)

Cluster ID	LLU - 70% incumbent max take-up	LLU - 60% max incumbent take-up	Bitstream Core - 70% incumbent max take-up	Bitstream Core - 60% incumbent max take-up	Bitstream MPoP -70% incumbent max take-up	Bitstream MPoP - 60% incumbent max take-up	WDM unbundling - 70% incumbent max take-up	WDM unbundling - 60% incumbent max take-up
1	9%	10%	4%	4%	6%	7%	4%	4%
2	10%	15%	3%	4%	5%	7%	3%	4%
3	24%	> 100%	4%	8%	8%	14%	6%	12%
4	25%	> 100%	5%	9%	10%	16%	6%	13%
5	> 100%	> 100%	16%	> 100%	28%	> 100%	92%	> 100%
6	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
7	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
8	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%

Table 3-23 shows the impact of setting 60% take-up as a maximum penetration level on wholesale prices. There is a similar increase of the prices in the range between 9% and 13% for all architectures. However, the overall effect on profitability differs between the competition scenarios due to the different shape of their cost curves.

Table 3-23: Impact of setting 60% take-up as target on wholesale prices (increase in %)

Cluster Type	P2P LLU	GPON Bitstream MPoP	GPON Bitstream Core	WDM PON Unbundling
Dense urban	9%	10%	10%	9%
Urban	11%	11%	11%	11%
Less Urban	12%	12%	12%	12%
Dense Suburban	12%	12%	12%	12%
Suburban	13%	13%	13%	13%
Less Suburban	13%	13%	13%	13%

Wholesale price increase

Our wholesale pricing has been determined endogenously as LRIC of the incumbent's cost at the maximum market share we have deemed reasonable to achieve. However, there can be different reasons why the wholesale price for the market will be higher than the "true" LRIC, such as risk premiums or asymmetric availability of information that prevent the regulatory authority from determining the real LRIC. A sensitivity was run that incorporates a 10% wholesale price mark-up to determine the impact on the business case of access seekers. Due to the flat cost curves of the wholesale scenarios and the dominant share of the access charge in the total cost of the access seeker a 10% wholesale price increase has a strong impact on viability. This holds especially true for the fibre unbundling case where again viable reach is reduced to the first two clusters.

Table 3-24: Impact of wholesale price increase on the critical market shares of access seekers

Cluster ID	Competitor (LLU)	Sensitivity LLU 10% mark-up	Competitor Bitstream Core	Sensitivity Bitstream 10% mark-up	Competitor Bitstream MPoP	Sensitivity Bitstream 10% mark-up	Competitor WDM PON unbundling	Sensitivity WDM un-bundling 10% mark-up
1	9%	10%	4%	4%	6%	7%	4%	4%
2	10%	14%	3%	4%	5%	6%	3%	4%
3	24%	> 100%	4%	7%	8%	12%	6%	10%
4	25%	73%	5%	8%	10%	14%	6%	11%
5	> 100%	> 100%	16%	> 100%	28%	> 100%	92%	> 100%
6	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
7	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%
8	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%	> 100%

CPE price sensitivity

As shown in section 3.2.2.2, CPE cost has a significant impact on total cost especially when deploying WDM PON (16% cost share) due to the higher equipment prices assumed. The base case in our models assumes that the WDM PON CPE is 50% more expensive than the GPON CPE, due to the more complex optical electronics. Given the current uncertainty about future CPE cost trends we have conducted a sensitivity analysis in which we assume three possible CPE price scenarios for the WDM architecture depending on the price of a GPON CPE: WDM CPE price two times higher than GPON CPE price, at GPON price level and lower than GPON price (75% of GPON CPE).

Table 3-25 analyses the impact of a CPE price variation on the incumbent's viability. Setting the price equal to GPON CPE price improves viability of WDM PON compared to all other architectures and along all clusters. This effect occurs stronger when setting the price below the GPON price level. An increase of the CPE price is as expected followed by an increase of the critical market shares, however, without having an impact on the number of profitable clusters. The influence of the three sensitivity scenarios on the competitor's viability is similar to the incumbent's case when looking at the critical market shares of the WDM unbundler (see Table 3-26). The competitor can expand his profitability by one cluster, if the price for CPE is set equal to or lower than the price for GPON CPE.

Table 3-25: Impact of WDM CPE price sensitivity on the critical market shares of incumbent

Cluster ID	WDM PON (base case, CPE price = 1.5*GPON price)	WDM PON (CPE price = 2*GPON price)	WDM PON (CPE price at GPON level)	WDM PON (CPE price = 0.75*GPON price)
1	25%	27%	23%	23%
2	39%	42%	36%	35%
3	50%	54%	46%	45%
4	49%	53%	46%	44%
5	63%	68%	59%	57%
6	72%	78%	67%	65%
7	> 100%	> 100%	94%	91%
8	> 100%	> 100%	> 100%	> 100%

Table 3-26: Impact of WDM CPE price sensitivity on the critical market shares of access seekers

Cluster ID	WDM unbundling (base case, CPE price = 1.5*GPON price)	WDM unbundling (CPE price = 2*GPON price)	WDM unbundling (CPE price at GPON level)	WDM unbundling (CPE price = 0.75*GPON price)
1	4%	5%	4%	3%
2	3%	4%	3%	3%
3	6%	9%	4%	4%
4	6%	10%	5%	4%
5	92%	> 100%	12%	9%
6	> 100%	> 100%	> 100%	> 100%
7	> 100%	> 100%	> 100%	> 100%
8	> 100%	> 100%	> 100%	> 100%

3.2.3 Investment and cost of different technologies – dynamic approach

Moving from a static to a dynamic approach, where the time path of investment according to a particular roll-out and the re-investment pattern is taken into consideration, has some impact on the relative investment and cost performance of the different architectures. We will first consider investment only and then analyse investment and cost.

3.2.3.1 Investment

In the dynamic analysis investments are spread over time depending on the timing of FTTH deployment in each cluster and the successive acquisition of customers. The main investment driver is the deployment of the outside FTTH plant from the user to the MPoP which defines the time of the investment peak. The total investment into passive and active network elements over the full 20-year period is shown in the following table. As in the static modelling GPON has the lowest and GPON over P2P the second lowest investments. Up to the third cluster WDM PON requires less investments than P2P, in clusters 4-6 P2P requires less invest. In the steady state WDM PON ranks second place in denser clusters. In the ramp-up WDM PON‘s total investment are higher due to CPE replacement invest (WDM CPE is most expensive).

Table 3-27: Undiscounted total investments over 20 years (mn Euro) and ranking (1 – lowest, 4 – highest)

Cluster ID	P2P	GPON over P2P	GPON	WDM PON
1	2,333 (4)	2,043 (2)	1,982 (1)	2,224 (3)
2	3,390 (4)	3,041 (2)	2,988 (1)	3,296 (3)
3	4,624 (4)	4,206 (2)	4,146 (1)	4,525 (3)
4	3,396 (3)	3,102 (2)	3,060 (1)	3,460 (4)
5	4,461 (3)	4,178 (2)	4,145 (1)	4,631 (4)
6	5,709 (3)	5,400 (2)	5,342 (1)	5,977 (4)
Total	23,914 (3)	21,970 (2)	21,661 (1)	24,113 (4)

The following figures (Figure 3-17 and Figure 3-18) show how undiscounted investments per year evolve for all architectures. Because the deployment path and subscriber acquisition is the same for all architectures the evolution of annual investments is also very similar for the four considered NGA architectures (examples shown for Cluster 1 and 6).

Figure 3-17: Annual investment – Cluster 1

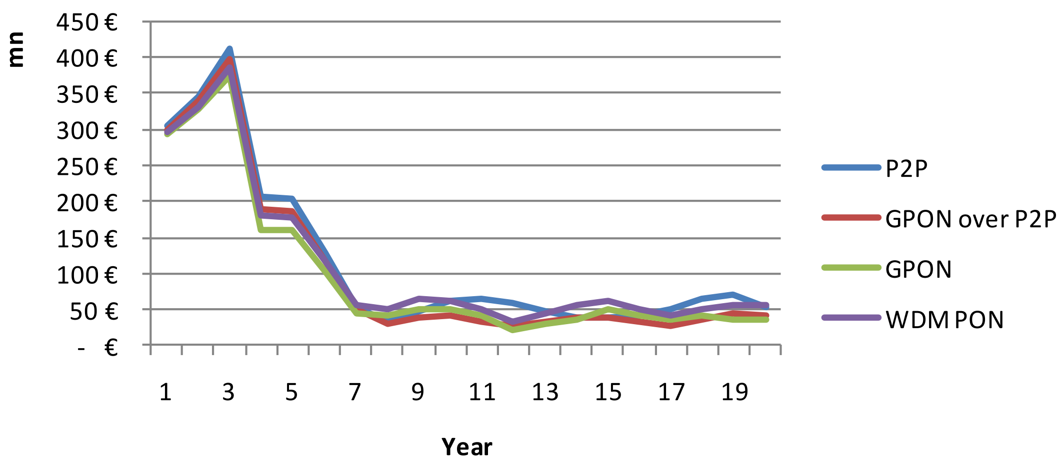
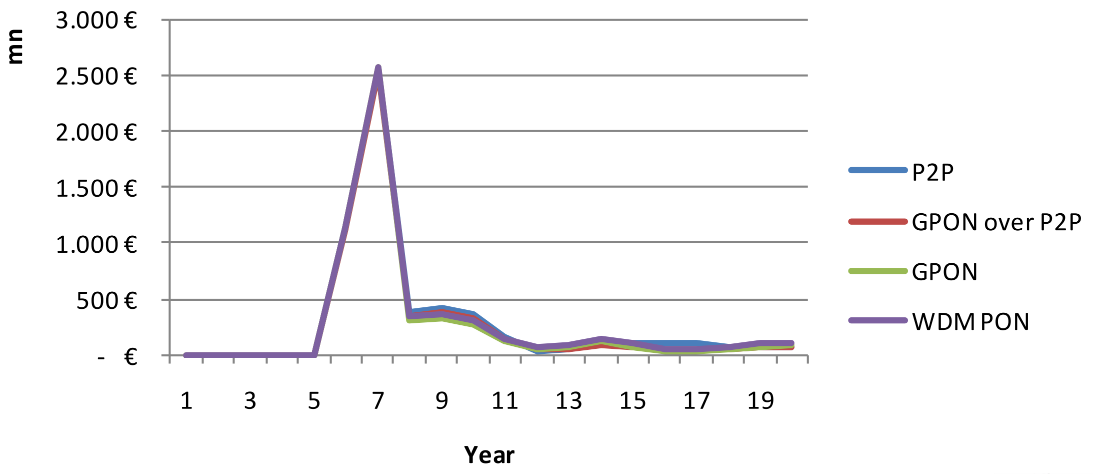


Figure 3-18: Annual investment – Cluster 6



Up to this point the effects of discounting future investments have not been considered. The following table shows the total investments at their present value (discounted at 10% p.a.). Discounting investments leads to an exchange of ranks for P2P and WDM PON.

Table 3-28: Discounted total investments over 20 years (mn Euro)

Cluster ID	P2P	GPON over P2P	GPON	WDM PON
1	1,427 (4)	1,317 (2)	1,257 (1)	1,354 (3)
2	2,138 (4)	2,009 (2)	1,961 (1)	2,086 (3)
3	2,936 (4)	2,784 (2)	2,739 (1)	2,892 (3)
4	1,970 (4)	1,867 (2)	1,843 (1)	1,923 (3)
5	2,290 (4)	2,197 (2)	2,164 (1)	2,238 (3)
6	2,652 (4)	2,556 (2)	2,531 (1)	2,611(3)
Total	13,414 (4)	12,729 (2)	12,496 (1)	13,104 (3)

Large parts of the total investment (inhouse and drop cabling account for over 70% of total investments) are actually the same for all architectures. In every case the majority of total investments is related to the network deployment in the early years. Therefore relative changes of cost differences occur if architectures are more or less “investment heavy” than GPON in the early years. This primarily depends on the share of investments directly tied to the network roll-out (happening earlier) as opposed to investments driven by subscriber acquisition (happening later). The following table provides an overview of network levels and their investment drivers.

Table 3-29: Investment relevance, driver and differences between architectures

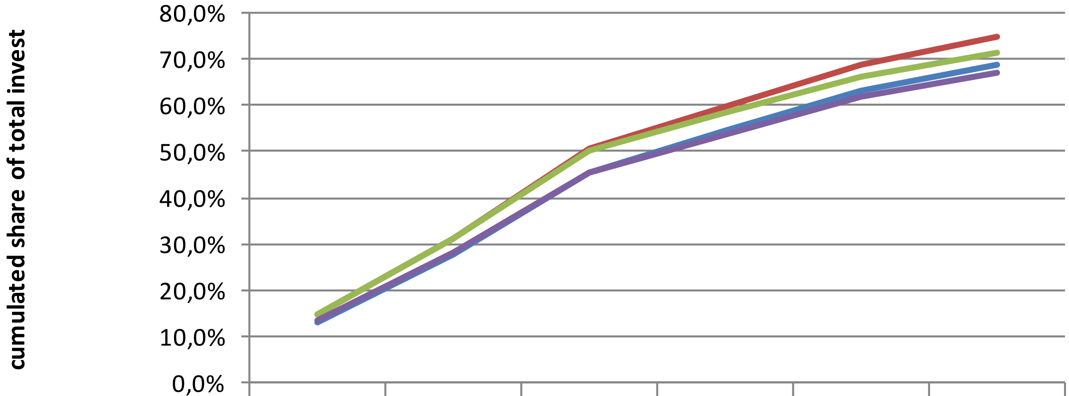
Network level	Relevance of total invest	Driver	Differences between architectures
Inhouse cabling	High (up to 36% of invest)	Subscriber	none
Drop cable	High (up to 60% of invest)	Homes passed	none
Distribution point	Low (less than 5%)	Homes passed	Only GPON and WDM PON
Feeder cable	Low in dense clusters (~5%), medium in less dense clusters (~13%)	Homes passed	Higher invest for P2P-topologies
MDF	Low	Homes passed	WDM PON only
Backhaul	Low-Medium (less than 10%)	Homes passed	WDM PON only
ODF	Low (less than 6%)	Homes passed (customer sided ports) Subscriber (network sided ports)	Higher invest for P2P-topologies
Active electronics at MPoP	Low-Medium (less than 10%)	Homes passed (GPON, WDM PON) Subscriber (P2P, GPON over P2P)	Higher for P2P

This explains why the time path of the investment differs to some extent between the architectures: Although most of the investment is front-loaded for all architectures, GPON has a smaller share of investment that is driven by the actual number of customers. While Ethernet ports in P2P are subscriber driven, GPON's investment in OLTs is not. The larger share of variable (customer driven) investment generates a slightly better risk profile for P2P compared to GPON.

WDM PON and GPON share the same passive network from the user's home to the former MDF location. WDM PON has a lower share of investments in the early years because even though OLTs for WDM PON are 5 times as expensive than GPON OLTs the high level of concentration means far less OLTs are required and overall the investment in OLTs is less than half that of GPON. Accordingly, even though the WDM OLT is an integral part of the early year roll-out driven investment, its investment share is lower than the GPON OLT equivalent. Because investment per CPE is 50% higher for WDM PON a higher part of the total investment is dependent on subscriber acquisition. The overall effect is a slightly lower share of investments for WDM in the early years.[65] Contrary to this the share of total investments for GPON over P2P in the first 6 years is slightly higher than GPON's (~74% Cluster 1). The reason lies in the additional investment into feeder and ODF ports which is completely driven by the network roll-out and not by subscriber acquisition and therefore occurs early.

65 Note that the reference in all cases is the share of total investments. We are not comparing absolute levels of investment, which – as we have shown earlier – are lowest for GPON.

Figure 3-19: Percentage of total investment during ramp-up (example Cluster 1)



	1	2	3	4	5	6
P2P	13,1%	27,9%	45,6%	54,4%	63,2%	68,7%
GPON over P2P	14,7%	31,3%	50,7%	59,9%	69,0%	74,7%
GPON	14,9%	31,3%	50,2%	58,4%	66,4%	71,5%
WDM PON	13,3%	28,3%	45,6%	53,7%	61,7%	66,9%

Year

To compare the impact of discounting investments we have computed the investment difference of the other technologies to GPON (which has the lowest investment level) and divided this by the investments into GPON. This was done for both discounted and undiscounted investments individually for each cluster and for the sum of clusters 1-6. Discounting future investment to a present value does not change the ranking between architectures. However, the relative differences to GPON decrease for P2P and WDM PON because they have a lower share of their total invest during ramp-up than GPON. Differences to GPON increase in case of GPON over P2P because it has a higher share of its total invest during ramp-up than GPON.

Table 3-30: Relative investment differences to GPON

Cluster	Sum of total invest P2P	P2P at present value	Sum of total invest GPON over P2P	GPON over P2P at present value	Sum of total invest WDM PON	WDM PON at present value
1	18%	14%	3%	5%	12%	8%
2	13%	9%	2%	2%	10%	6%
3	12%	10%	1%	2%	9%	8%
4	11%	7%	1%	1%	8%	4%
5	8%	6%	1%	1%	6%	3%
6	7%	5%	1%	1%	6%	3%
Total	10%	7%	1%	2%	8%	5%

When interpreting Table 3-30 one has to keep in mind that the roll-out is focused on the denser clusters first (Cluster 1 finished in year 3) and less dense clusters are finalised later (Cluster 6 fully covered in year 8).

3.2.3.2 Cost

The analysis now considers present values of investment, their associated OPEX and direct costs which are floorspace rental, energy, concentration and core network as well as retail costs ("total expenses"). We are hence looking at the expense side of the operator's cash flow. This once again does not change the overall ranking of architectures: GPON remains the lowest cost technology, GPON over P2P comes next[66] followed by WDM PON and P2P. The differences between technologies decrease when comparing total (discounted) expenses and investment.

Table 3-31: Ranking of architectures relative to lowest total expenses over 20 years at present value (1: lowest expenses, 4: highest expenses)

Cluster	P2P expenses at present value	GPON over P2P expenses at present value	GPON expenses at present value	WDM PON expenses at present value
1	4	3	1	2
2	4	2	1	3
3	4	2	1	3
4	4	2	1	3
5	4	2	1	3
6	4	2	1	3
Total	4	2	1	3

The following table shows details for the total cost over clusters 1-6 at present value.

66 Exception: In the dense urban cluster WDM PON ranks second.

Table 3-32: Present value of invest and cost over 20 years – Cluster 1-6

Invest + OPEX + Common Cost at present value	**P2P expenses at present value**		**GPON over P2P expenses at present value**		**GPON expenses at present value**		**WDM PON expenses at present value**	
CPE	1,926,728,564 €	8%	2,215,737,848 €	10%	2,215,737,848 €	10%	3,323,606,773 €	15%
Inhouse cabling	2,947,101,520 €	13%	2,947,101,520 €	13%	2,947,101,520 €	14%	2,947,101,520 €	13%
Passive network up to ODF (incl. floorspace invest for active equipment)	11,102,838,544 €	48%	11,102,257,961 €	51%	11,041,790,729 €	51%	11,108,317,322 €	50%
Network sided ODF port + patch cabling + splitter for GPON over P2P	289,102,242 €	1%	492,454,531 €	2%	9,188,345 €	0%	762,996 €	0%
P2P Ethernet ports	1,951,903,720 €	8%	0 €	0%	0 €	0%	0 €	0%
PON OLT & PON Ethernet ports	0 €	0%	316,036,416 €	1%	647,543,196 €	3%	335,038,558 €	2%
Direct Cost + Common Cost at present value								
MPoP energy	105,818,479 €	0%	26,687,866 €	0%	60,211,705 €	0%	18,755,358 €	0%
Floorspace rental	124,140,573 €	1%	122,949,414 €	1%	52,330,097 €	0%	1,388,713 €	0%
Concentration/backhaul network	381,658,132 €	2%	381,658,132 €	2%	381,658,132 €	2%	168,239,087 €	1%
Core network	1,190,313,113 €	5%	1,190,313,113 €	5%	1,190,313,113 €	5%	1,194,003,373 €	5%
Retail	3,112,308,200 €	13%	3,112,308,200 €	14%	3,112,308,200 €	14%	3,112,308,200 €	14%
TOTAL EXPENSES	**23,131,913,086 €**	**100%**	**21,907,505,000 €**	**100%**	**21,658,182,884 €**	**100%**	**22,209,521,899 €**	**100%**

There are significant differences between architectures regarding energy and floor-space rental: P2P has 2 times higher energy cost than GPON and nearly 6 times higher costs than WDM PON. P2P also has about 2.5 times higher floorspace rental cost than GPON and about 90 times more than WDM PON. However, the weight of these elements is negligible (not more than 1%) in the overall cost comparison. On the other hand, retail and core network cost which account for close to 20% of the total expenses are identical for all architectures. This explains why the differences between architectures decrease significantly compared to the pure investment analysis.

We have applied the same methodology to analyse the differences between architectures that was used in the previous section on investment (total expense difference of e.g. P2P to GPON divided by the total expenses of GPON). Results are shown in the following table.

Table 3-33: Cost difference to GPON: Total expenses (invest and OPEX, direct and common costs) at undiscounted and present value

Cluster ID	P2P sum of expenses	P2P expenses at present value	GPON over P2P sum of expenses	GPON over P2P expenses at present value	WDM PON sum of expenses	WDM PON expenses at present value
1	12%	11%	2%	3%	3%	2%
2	10%	8%	1%	2%	4%	3%
3	9%	7%	1%	1%	3%	3%
4	8%	6%	1%	1%	4%	3%
5	7%	6%	1%	1%	3%	2%
6	6%	5%	1%	1%	3%	2%
Total	8%	7%	1%	1%	3%	3%

The direction of the impact of discounting total expenses generally remains the same as in the sole analysis of investments. The spread between GPON and P2P or WDM PON decreases. The spread between GPON and GPON over P2P increases. Again, we find it especially interesting that GPON over P2P remains only slightly more expensive than GPON. In relative terms, the difference measured in present value of discounted expenses between GPON and GPON over P2P becomes negligible (~1%); P2P generates ~7% more expenses (Cluster 1 to 6), than GPON; WDM PON 3% higher expenses.

3.2.3.3 WDM PON sensitivity: Revenues from sale of MDF locations

The incumbent might realise windfall profits when selling former MDF locations. Such windfall profits are not part of the decision relevant costs of a certain architecture. They have, however, to be taken into account in the decision making process of the investor. This is of particular relevance, if such windfall profits are different among architectures.

Windfall profits can conceptually consistently be integrated into our dynamic discounted cash flow analysis. They simply diminish the discounted total expenses of a particular architecture. In this model MDF dismantling only occurs in the case of WDM PON. We have assumed that the sales revenue per MDF location is higher in the denser cluster than in the less dense clusters. One-time profits are realised after the former copper network is switched off. We have assumed that this will occur one year after the maximum penetration in a cluster is reached to reflect a certain delay, e.g. to ease the transition for competitors. Given our deployment path this means that the incumbent realises these net revenues in year 8 (Cluster 1) earliest and in year 12 (Cluster 6) latest. The following table shows the net revenues per MDF, per cluster and discounted net revenues per cluster.

Table 3-34: Sales from MDF dismantling

Cluster	net revenue per dismantled MDF (mn)	Dismantled MDFs	Net revenue from MDF dismantling per cluster (mn)	Discounted net revenue per cluster (mn)
1	2.0 €	65	130.0 €	60.6 €
2	1.0 €	163	163.0 €	69.1 €
3	0.5 €	246	123.0 €	52.2 €
4	0.4 €	276	110.4 €	42.6 €
5	0.3 €	298	89.4 €	28.5 €
6	0.2 €	411	82.2 €	26.2 €
Total			698.0 €	279.2 €

We have subtracted the discounted net revenues from the present value of WDM PON total expenses, working under the assumption that these revenues can fully be used to improve the WDM PON business case. When comparing this modified present value of total expenses WDM PON actually ranks first place with lowest discounted expenses in Cluster 1, so it actually becomes cheaper than GPON. WDM PON also overtakes GPON over P2P in Cluster 2 and ranks second after GPON. In all other clusters WDM PON remains in third place but the difference to GPON decreases.

Table 3-35: Comparison of discounted total expenses (mn Euro)

Cluster	P2P expenses at present value	GPON over P2P expenses at present value	GPON expenses at present value	WDM PON expenses at present value	WDM PON expenses at present value reduced by present value of MDF sales revenue, (ranking)
1	2,735 €	2,539 €	2,469 €	2,520 €	2,459 € (1)
2	3,735 €	3,504 €	3,452 €	3,553 €	3,484 € (2)
3	4,988 €	4,717 €	4,672 €	4,795 €	4,743 € (3)
4	3,426 €	3,242 €	3,218 €	3,312 €	3,269 € (3)
5	3,859 €	3,689 €	3,655 €	3,745 €	3,717 € (3)
6	4,390 €	4,216 €	4,192 €	4,285 €	4,258 € (3)
Total	23,132 €	21,908 €	21,658 €	22,210 €	21,930 € (3)

This is not only because dismantling revenues are higher in the denser clusters and discounted less because they occur earlier. Considering the spread between GPON and WDM PON the undiscounted MDF revenue potential only suffices to close the gap in clusters 1-3. In clusters 4-6 the gap between GPON and WDM PON total expenses at present value is higher than the undiscounted sales revenues from MDF dismantling. Therefore WDM PON cannot take the first place even when considering MDF sales revenues and also does not gain enough to overtake GPON over P2P even though the spread is reduced.

3.2.4 Summary of cost modelling results

3.2.4.1 Profitable coverage, investment, cost and competition in the steady state analysis

If we assume that the fixed network can reach a market share of up to 70% of the total potentially addressable market (access lines), an incumbent operator can profitably cover a significant part of Euroland with FTTH (about 50% of the population could be covered with P2P or WDM PON, about 64% could be covered with GPON over P2P and GPON).

Theoretically, a FTTH infrastructure can be replicated by a second investor only in the Dense Urban Cluster 1 or for about 8% of the population. In all other viable areas the FTTH investor needs a critical market share of close to or above 50% to become profitable which makes replicability impossible.

In the relevant clusters 1-6 the cost comparison of our four architectures has shown the following results: GPON is the cheapest technology, followed by GPON over P2P, WDM PON and P2P. With the exception of Cluster 1 where WDM PON and GPON over P2P switch ranks, this is consistent over the relevant clusters.

Lower investment requirements in a Brownfield approach enable incumbents to increase the profitable coverage with P2P and WDM PON up to the Less Suburban Cluster 6. Utilizing existing duct infrastructure benefits the two point-to-multipoint architectures GPON and WDM PON most, because they have fewer fibres in the feeder and backhaul segments and hence a higher chance of avoiding civil works. The investment savings by segment are as follows:

- The effective reduction in the drop segment ranges from 7% to 20% depending on the cluster, and is the same for all architectures, since the architectures do not differ in this segment.
- In the feeder segment, the savings for P2P are around 7% and for GPON around 40%.
- The savings in the backhaul segment amount to around 40% for WDM PON.

The segment specific savings in investment translate to overall cost savings of 5% (Cluster 1) to 11% (Cluster 8) for the WDM PON architecture which benefits most. Cost savings for GPON are higher than for P2P but lower than for WDM PON, and range from 5% (Cluster 1) to 9% (Cluster 4). The lowest cost savings occur with P2P from 4% (Cluster 1) to 7% (Cluster 3).

Should WDM PON vendors be able to reduce CPE prices to the level of GPON CPE the viability of WDM PON could be extended by one cluster to Cluster 6. In addition the critical market shares for viability could be reduced although not more than by 2-4%-points.

Competition cannot follow the incumbent in all areas of the FTTH roll-out. Independent of the network architecture and the access scenario considered, the viability of any competitive model ends at least one cluster less than the viability of the incumbent’s roll-out. The critical market shares of the different scenarios indicate that in all architectures and competition scenarios potentially several competitors could survive in the market. The highest potential number of competitors may occur in the case of bitstream access and wavelength unbundling at the core.

As expected, business models on the basis of unbundling require (significantly) higher critical market shares than business models based on bitstream access. The unbundling model requires already a critical market share of 24% in Cluster 3, while bitstream access is viable at 4% to 8% critical market share in the same cluster.

Because the cost curve of competitors is relatively flat in the relevant range, only slight changes in the relevant parameters (e.g. ARPU) have a strong impact on the profitability. In case of unbundling, for instance, the critical market share jumps from 10% in Cluster 2 to 24% in Cluster 3. The structure of the cost curves in the relevant range makes unbundling a riskier business model than bitstream access.

If the wholesale prices also reflect the investment savings of the incumbent (Brownfield case) costs and critical market shares of competitors decrease in all competition scenarios. In addition, they can also expand competitive coverage by one cluster with the exception of the LLU scenarios.

We have calculated the impact of deviations from LRIC based wholesale prices on the structural conditions of competition. Under the assumption of fixed ARPUs even a moderate increase of the wholesale prices by 10% reduces the viability of competition and the competitive coverage in most cases. The most significant impacts occur in the LLU unbundling scenarios. Critical market shares of competitors in all scenarios increase significantly.

3.2.4.2 Impact of the ramp-up on costs and technology ranking

Taking a particular roll-out and the re-investment pattern into account, the relative performance of the architectures is somewhat impacted because of different time paths of investment. Although most of the investment is front-loaded for all architectures, a lower part of the GPON investment is driven by the actual number of subscribers. While Ethernet ports in P2P are subscriber driven, GPON's investment in OLTs is not. The larger share of variable (subscriber driven) investment generates a slightly better risk profile for P2P compared to GPON.

However, the overall relative performance only changes moderately: GPON remains the lowest cost technology, GPON over P2P comes next followed by WDM PON and P2P. The differences between technologies, however, decrease if comparing total (discounted) expenses and investment. In relative terms, the difference in terms of present value of discounted expenses (Cluster 1 to 6) between GPON and GPON over P2P become negligible (~1%); P2P generates ~7% more expenses than GPON and WDM PON ~3% more.

As in the static modelling single cost items like energy and floor space exhibit significant differences among architectures. P2P causes nearly double as much energy cost at the MPoP as GPON and nearly 6 times higher energy costs than WDM PON (in terms of present value). P2P has more than 2.5 times higher floor space costs than GPON and even nearly 90 times more than WDM PON. These huge differences, however, have only a very limited impact on the overall cost performance of architectures because the cost share of each of these factors is not more than 1%.

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Annex 1: Key parameters of cost modelling

Civil engineering parameters

In our model we consider duct and aerial deployment as possible deployment forms (no direct buried lines were assumed). Duct construction cost are highest in the dense populated areas and amount to 100 € per m in Cluster 1, while decreasing to 60 € per m in the last two clusters. Contrarily, aerial deployment costs are assumed to be equal for all clusters (15 € per m), however, aerial cabling is not used in the two densest clusters but is deployed to a larger degree in the rural clusters (up to 60%). Aerial deployment is only relevant for the drop segment, in the feeder and backhaul segment all cables are deployed in ducts.

Furthermore, we assume an invest of 548 € per distribution sleeve and 860 € per manhole along all clusters and segments.

Port prices

Based on discussions with equipment vendors and on WIK's modelling experience we have defined port prices for the active equipment installed at the MPoP. The following table provides an overview of the prices assumed.

Table A-1: Port prices for active equipment

	1 Gbps Ethernet port	10 Gbps Ethernet port	Standard OLT port	WDM OLT port
Invest per port	120 €	2.000 €	1.000 €	5.000 €

ODF

The fibres coming from the outside plant are terminated on the customer sided ports of an ODF in the MPoP and are accessible per patch cables. We assume a price of 23 € per ODF port and 11 € per patch cable.

In case of fibre unbundling the competitor places an additional ODF of his own at rented collocation space in the MPoP where he operates his own Ethernet Switch. The competitor's ODF is connected via connection cable to dedicated customer sided ports of the incumbent's main ODF. Therefore, we assume a higher price for the competitor's ODF port (46 €).

Energy consumption

We have assumed average energy consumption on a per port per month basis. Energy consumption per port is higher for WDM PON than for GPON OLTs and higher for

10Gbps Ethernet ports than for 1Gbps ports. The price per kWh of energy is set to 0.16 €. The energy consumption and the resulting cost for the different active equipment items are shown in Table A-2. We have not considered the energy consumption of CPEs because the subscribers bear energy cost themselves.

Table A-2: Energy consumption and cost

	1 Gbps Ethernet port	10 Gbps Ethernet port	Standard OLT port	WDM OLT port
Energy consumption per month (kWh)	1.08	14.4	14.4	43.2
Energy cost per port per month (€)	0.17	2.30	2.30	6.91

CPE prices

The prices for equipment installed at customer's premises depend on the access architecture deployed. We have assumed a price of 100€ for the P2P router and 115€ for a GPON ONT. In our base case we assume that the WDM PON CPE is 50% more expensive (172.5 €) than the GPON CPE due to the more complex optical electronics required.

Annex 2: NGA technologies not considered

FTTN/VDSL

With FTTNode/VDSL (also FttCurb) the copper access lines are shortened and already terminate at the street cabinet as the feeder segment between MPoP/MDF and street cabinet is replaced by fibre. Because the remaining copper segment is shorter – it now only consists out of the drop cable segment sub-loop (Figure 2-2) -, higher bandwidths can be realised, e.g. with VDSL technology. The street cabinets need to be upgraded to host DSLAMs (energy, air condition etc.), which terminate the electrical copper signal and concentrate it in an Ethernet protocol over fibre up to the MPoP.

Since the distance between the DSLAM in the street cabinet and the Ethernet switch in the MPoP, the feeder cable segment, is no longer limited by copper transmission characteristics it may become longer than before. Accordingly, MDF locations could be closed down, or remain as a mere infrastructure node point because of the existing duct infrastructure, and be replaced as an active node by an MPoP further up in the network.

Because VDSL technology still bases on a copper sub-loop it is still dependent on copper loop length and line quality. The available bit rates of VDSL are very much dependent on the length of the copper line[67] and the advantages of VDSL regarding bandwidth over ADSL disappear at sub-loop distances of more than 500m. In addition the transmission characteristics of copper lines vary strongly and also depend on cross talk effects of neighbouring pairs. Compared to FTTH technologies performance of FTTN therefore is very heterogeneous and falls far behind the potentials of a full fibre based loop.[68]

We have excluded this architecture from our considerations due to its poorer performance compared to FTTH.

DOCSIS 3.0

Data Over Cable Service Interface Specification (DOCSIS) is the standard according to which data and voice signals are transmitted in parallel over the existing cable-TV networks. The up to date standard is DOCSIS 3.0, which allows for up to 400 Mbps down and 108 Mbps upstream capacity[69] in a shared channel. A group of customers is connected to an active fibre node by the existing coaxial cable distribution (access) net-

67 See Wulf (2007) or Williamson/Klein/Reynolds/Jones (2008).

68 VDSL technology reaches 40Mbps downstream and more over distances of up to 1km. For longer distances the bandwidth decreases significantly. Over short loops below e.g. 250m bandwidth might even realize up to 100Mbps. The upstream bandwidth is typically below half of the downstream bandwidth. Typical sub-loop lengths strongly depend on country specific copper access network design and may be longer than 1 km for a significant number of customers.

69 EuroDOCSIS 3.0 with all bundle options for up- and downstream channels, thus being the maximum capacity.

work. The fibre node is connected via fibre lines to a central Cable Modem Termination System (CMTS), where the voice/data signals will be separated from the TV-Signals (RF-TV). Using Figure 2-2 as a generic reference the coaxial cable is in the drop cable segment, the fibre node is located in the splitter and the CMTS is located in the MPoP. Thus the DP is the point where the transmission media changes from coaxial cable to fibre, and many customers are concentrated to that fibre. Communication is organized comparable to GPON by administering the communication and possible communication conflicts by the CMTS instead of the OLT. Bandwidth per end customer is determined by the number of end customers per fibre node. A typical relation of today is spread between 2000 and 70 end users per node. The maximum average bandwidth per end customer then can reach 5.7 Mbps maximum.

In many areas of Europe the coaxial cable-TV networks are an already existing communication infrastructure which can be or already is upgraded to bidirectional communication as alternative to the classical telecommunication networks. A natural migration path towards higher bandwidth is increasing the number of fibre nodes and moving them closer to the end customer, until they end in FTTB and FTTH solutions. This can be done in a smooth process of incremental steps for single network segments, not requiring large one time investments. This is an advantage of the already existing operators.

A new entrant will not invest in coaxial cable infrastructure, but would deploy a GPON FTTB/FTTH architecture with RF channel if he wants to come close to the cable-TV business models.

Since the bandwidth per end customer is a magnitude lower compared to the FTTH architectures we consider and because technology and business model will be migrated to GPON when infrastructure is upgraded for bandwidth increase, we did not include the DOCSIS 3.0. architecture in our analysis.

Active Ethernet

In Active Ethernet architectures a concentrating Ethernet switch is placed between the MPoP and the customer location, e.g. in a cabinet at the distribution point (Figure 2-2). The drop cable segment consists of dedicated fibres per home and the feeder segment needs only very few fibres, one per Ethernet switch at the DP. Similarly to FTTN/FTTC the intermediate location in the field (e.g. the distribution point) requires energy and air condition to host the active switch.

Typically this architecture allows one to offer 100 Mbps symmetrical traffic per end customer home, which will be overbooked at the first Ethernet switch, who manages the shared use of the feeder fibre. Compared to an Ethernet P2P solution this approach is less flexible to offer higher bandwidth for individual customers, because switches with all speed ports are more expensive and the smaller spaces at the DP do in most cases not allow for a second high speed switch at this location and anyhow such a switch would not scale very well. Thus Active Ethernet is based on a Point-to-Multipoint fibre plant with all the inflexibility for future use as already described above.

The primary advantage of this architecture is the savings on feeder fibre count and potentially MPoP floorspace due to ODF and switch port reduction. However, that is very likely more than outweighed by the cost of active distribution points (switches, cabinets, energy…). Since decentral switches also increase operation cost for service and maintenance, these architectures of the early FTTH roll-out are no longer implemented in new deployments – at least to our knowledge.

We have therefore excluded this architecture from this study due to its poorer performance compared to Ethernet P2P and its expected higher cost.

Multi-fibre deployment

Multiple-fibre architectures deploy more than a single fibre per home, e.g. four as in the Swisscom approach, in the drop cable segment and (optionally) in the feeder cable segment. This is a risk sharing strategy option that allows several co-investors to share the investment into NGA and obtain parallel access to the same end customer. Basic thinking behind this approach is that even if the total investment for multiple fibres in the drop segment is higher, sharing the invest reduces the investment per investor compared to a single fibre approach.

The investing operator connects at least one fibre per home to its ongoing feeder network up to the MPoP. The second to fourth operator each shares fibres in the drop cable segment to the end customer homes and in principle has the choice to connect these fibres to its own separately ducted feeder network (e.g. local power utility ducts) at the Distribution Point or to also share fibres in the feeder infrastructure up to the MPoP and collocate there.

The Multi-fibre approach in the drop cable segment still allows one to deploy a fibre Point-to-Point or fibre Point-to-Multipoint architecture for the customer access, depending on how many fibres the different investors deploy in the feeder segment. In Switzerland the typical architectures as far as we know are based on Point-to-Point fibre plants.

We have analysed the implications of multi-fibre deployment already in our 2009 studies for ECTA[70] and have assessed the advantages and disadvantages as a competitive approach in more detail in a study for the Swiss regulator BAKOM[71].

Including the Multi-fibre approach within this study would have complicated it and at least duplicated the amount of scenarios considered. But the general results of the stud-

70 See Ilic/Neumann/Plückebaum (2009).
71 See Ilic/Neumann/Plückebaum (2010).

ies mentioned can also be transferred, thus we exclude the Multi-fibre consideration here.

FTTB

In FTTB architectures the complete copper loop down to the basement of the end customer buildings is replaced with fibre but the inhouse cabling remains the already existing copper or coax-based infrastructure. Mini-DSLAMs or ONUs can serve as fibre termination nodes in the building basement. Each building therefore only requires one fibre in the generic FTTB architecture thus reducing the fibre count strongly not only in the feeder but also in the drop segment.

FTTB can be deployed on top of a Point-to-Point or Point-to-Multipoint fibre plant, resulting in different savings of the fibre count in the feeder segment. Based on a Point-to-Multipoint fibre plant the savings are higher, but require a GPON technology to administer the traffic. FTTB Point-to-Point has individual fibres per building, thus allowing one to connect each building with an individual connection, as requested by the potential customers inside, and enabling a higher degree of flexibility for future upgrades.

FTTB also means that the maximum capacity of each user is limited by the bandwidth provided to the building and the number of other subscribers in the same building. In the near future 1Gbps, 2.5 Gbps or 10 Gbps links may still be sufficient for common European Multi-Dwelling-Unit compositions. However, as the number of tenants per building increases, the access link bandwidth per user that can be guaranteed decreases. In the long term FTTB architectures might need to be migrated to FTTH to allow sufficient bandwidths. Therefore, FTTB could be considered as an alternative to FTTC when migrating from copper based loops to FTTH, already now allowing for higher bandwidth and more stable product quality. Upgrading to FTTH, however, can only be efficiently done when considering at least ducts in the drop segment with sufficient space for further fibres, like there are potential customers.

As we have taken a rather forward looking approach we have decided to only assess FTTH solutions, which exclude any copper cable complexities and product quality dependency.

EPON

There are a variety of standards that define the communication of active electronics on a Point-to-Multipoint FTTH fibre plant. However, of the many (TDM) PON systems proposed only GPON (Gigabit PON) and EPON (Ethernet PON) have been used for mass deployment. Some characteristics of GPON in comparison to EPON are shown in Table A-3. Due to the fixed time interval based administration procedures of bandwidth allocation in GPON it is better suited to support TDM connections to dedicated customers, thus allowing more end customer flexibility than EPON.

Concerning fibre count and characteristics of the use of Point-to-Multipoint vs. Point-to-Point fibre plants there is no difference between both technologies.

In this study we therefore have exclusively referred to the GPON standard because it is the dominant technology applied in Europe and the US. EPON as far as we can see has no relevance for future FTTH deployment in Europe.

Table A-3: Comparison of PON standards

	GPON	EPON
Standard	ITU-T G.984	Ethernet-First-Mile standard, IEEE 802.3ah
Deployed in	Europe, USA	Japan, Korea
Capacity	Up to 2.5Gbps down, up to 1.25 Gbps up	1.25Gbps symmetrical
Max splitting	1:64, in future 1:128	1:32
Protocols supported	Ethernet, TDM, ATM	Ethernet
Max reach	20km 60 km (in future)	20km more (in future)

Source: WIK-Consult

Annex 3: Results in the literature related to NGA

Insights from earlier work on telecommunications markets partly apply to an NGA context. A number of works on one-way access concern optimal access prices set by a regulator in a second-best sense (Ramsey pricing), i.e. respecting the participation constraints of the firms involved. Most of these works consider homogeneous services on the retail market. Other works modify the assumption that all services are homogeneous and postulate that there are two types of firms, the incumbent with market power and a set of firms who act as a competitive fringe, i.e which offer homogeneous services among themselves and thus do not possess market power. In such frameworks the literature has formulated rules according to which access should be granted for given retail prices. In particular, the "efficient component pricing rule" (ECPR) received a lot of attention. It says that entrants should pay access charges equal to the incumbent’s direct costs of access plus the opportunity costs of profit contributions forgone by the incumbent in selling access rather than selling to end-users.[72] For optimality this approach requires entrants to have no market power downstream. The works on the ECPR are not directly relevant to our context since our aim is to consider various firms that can exert market power.

Quite a large literature exists on unbundled access (motivated by developments in the European context). We refer to Gual und Seabright (2000), a contribution that was made at the request of DGCOMP at the European Commission, and de Bijl and Peitz (2005) which provide overviews over relevant economic issues, in particular from the view point of a regulator. Unbundled access tries to strike a balance between the interests of the owner of the access network and other parties who seek access. In the absence of externalities privately negotiated solutions may implement the efficient solution. However, in the presence of externalities the owner of the access network may have an incentive to refuse access by third parties. Mandated access is then needed to allow for competition and to assure that inefficient bypass is avoided.

Few works allow for imperfect competition at the retail level, arguably a key feature in actual telecommunications markets. Some of these shall be briefly disscussed below. Laffont and Tirole (1994) investigate a Ramsey price setting that includes the access price in a market with an imperfectly competitive retail segment. Ramsey pricing leads to higher markup in market segments in which demand is rather inelastic. Armstrong and Vickers (1998) consider an imperfectly competitive and possibly asymmetric market in which one of the two firms is more efficient. They show that optimal regulation has an, at first sight, surprising feature: The one-way access price should be used such that the more efficient firm obtains an even larger market share than absent regulation. This is due to the fact that in the type of differentiated product models commonly analyzed, the unregulated market outcome features a larger market share of the *less efficient* firm than what is socially optimal.

72 For an elaborate discussion, see Armstrong (2002); see also Laffont and Tirole (2000) and Vogelsang (2003).

De Bijl und Peitz (2006) distinguish between two types of models, a “Hinterland” and a “No-Hinterland” model. In the No-Hinterland model total demand for subscription is fixed. This implies that all potential consumers are subscribers. A higher price level that leaves market shares unchanged amounts to a transfer of rents from consumers to firms, while total welfare remains constant. By contrast, in the Hinterland model some consumers are captive in the sense that they only consider subscribing to one particular network operator. However, these consumers are, as a group, sensitive to price changes: The higher the price charged by a network operator the more consumers who are captive to this operator decide to abstain from the market. In effect, total demand depends on prices, and a higher price level that leaves market shares unchanged is *not* welfare neutral. Here, such a higher price level leads to a deadweight loss.

De Bijl and Peitz show that allocative and welfare effects critically depend on the type of model. In particular, in the No-Hinterland model the access price is neutral to the allocation and to the equilibrium profit of the entrant. This implies that the entrant’s investment incentive are not affected by access regulation. This general neutrality result breaks down in their Hinterland model (which they develop in a duopoly context) because total demand is price elastic and thus higher access prices that leave the entrant’s mark-up as well as its market share in the competitive segment unchanged are not neutral to the entrant’s profit. In the No-Hinterland model an access regime that is more favorable to the incumbent simply shifts rents from consumers to the incumbent. From a static consumer welfare perspective regulating access prices at marginal costs is called for. However, from a dynamic perspective the regulator has to allow for rents on the incumbent’s side because otherwise the investment will not be undertaken.

While the neutrality result is interesting as a theoretical insight, it does not apply to markets in which some consumers stay with a non-NGA provider. Therefore, the de Bijl/Peitz No-Hinterland model is conceptually different from the No-Hinterland model developed below because we here allow for a separate cable operator as one of the market participants, with the effect that the neutrality result for NGA services does not hold in any of our models. In general, a less favorable access regime for the entrants will result in lower entrants’ profits, affecting the entrants’ investment incentives.

While existing work on one-way access can uncover some economic forces at play, they cannot be directly linked to real-world markets because they are too stylized. Two important aspects are missing: 1) flexibility with respect to the number and nature of market participants and 2) flexibility with respect to cost and demand characteristics reflecting the asymmetries between market players. We provide such a flexible approach which, furthermore, allows for a variety of alternative regulatory regimes.[73]

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73 In a different context, Hoernig (2010) developed a model which shares with the present analysis the features that it allows for market asymmetries and a finite number of market players. However, this framework is not directly applicable because of different institutional features and the focus on two-way access prices.

With respect to investment incentives, it is important to recall the, in general, ambiguous link between the realized level of investments and the intensity of competition in the product market. This line of research has been initiated by Arrow (1962).[74] An important insight in this literature is that an incumbent firm which replaces an older technology may have weaker investment incentives than a newcomer because it replaces its existing profits from the old technology. This so-called replacement effect tends to lead to weaker investment incentives by an incumbent firm. However, in a context with entry, a sucessful entrant may largely destroy the incumbent's profits due to the superiority of its new technology. Because of this, the incumbent may have stronger incentives to invest than an entrant. While most works on telecommunications markets take the investment decisions as given, these works can be extended to include such considerations.[75] To evaluate investment incentives, one has to consider differential profits that are due to the investment under consideration. Results are rather straightforward if, as we assume for FTTH infrastructure, only one of the firms has the option to invest. In this case, when comparing profits resulting in the absence of the investment to those when the investment has been made, access regulation that leads to an increase in profits can be considered as regulation that stimulates investments. If more than one operator can invest, the exact nature of the investment game has to be specified. There are a number of formal theoretical investigations that explicitly consider such links between one-way access and investment incentives.

First, several works analyze the incumbent's incentives to increase the quality of its access network.[76] In particular, Foros (2004) is concerned with regulation as a means to achieve efficient investment and to avoid foreclosure of the firm seeking access. Second, Gans (2001), Gans and King (2004), Hori and Mizuno (2006, 2009), and Vareda und Hoernig (2010) analyze the incentives of two firms in an investment race to establish an access network. Third, Bourreau und Dogan (2005) analyze a dynamic model to investigate the entrant's incentives to invest in its own access network. Here, the incumbent strategically grants access to delay the investment by the entrant.

Our focus will be on market outcomes for given investments that are based on the cost-modelling results (see chapter 3). However, our approach will allow us to quantify the gains from certain investment decisions. Thus, it can also shed some light on investment incentives of the different market players. Furthermore, we can evaluate the effect of regulation on these gains from investment.

74 For a first introduction into this topic, see chapter 18 in Belleflamme und Peitz (2010).
75 For discussions and overviews see Valletti (2003), Guthrie (2006), and Cambini und Jiang (2009).
76 See Foros (2004), Kotakorpi (2006), Vareda (2009a, 2009b), Brito et al. (2008, 2010), Klumpp and Su (2009) and Nitsche and Wiethaus (2009).

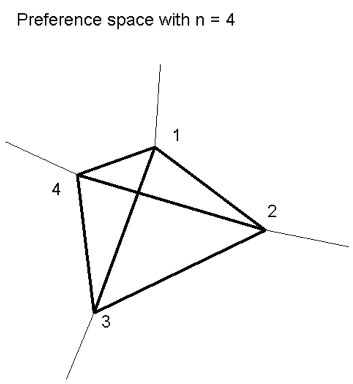
Annex 4: The competition models: Formal derivations

Hinterland model

Preference space

There are two consumer segments, N_c "Competitive" consumers who opt between pairs of networks, and N_e "captive" ones who either adhere to one network or do not subscribe. There are $n \geq 2$ networks, each at one of the n nodes of a complete graph of size N_c which describes competitive consumers' space of preferences over which they are uniformly distributed. The distance between two nodes is $l = 2N_c / n(n-1)$. All competitive consumers subscribe to some network. Horizontal differentiation is modelled in Hotelling fashion through a linear transport cost td , where $t > 0$ and d is the distance between the subscriber and his network. Higher t is interpreted as originating from more horizontal differentiation due to more varied offers by networks. Below we will let transport costs differ between pairs of networks, with $t_{ij} = t_{ji} > 0$.

Captive consumers are located on additional rays of size R_i , each emanating from the node of network i (This is the Hinterland model of elastic subscription demand generalized to multiple asymmetric backyards), with $\sum_{i=1}^{n} R_i = N_e$. In each Hinterland, some $y_i \leq R_i$ consumers will subscribe in equilibrium. On Hinterland i , consumers have a transport cost of $\tau_i d$, where d is the distance to network i .



Subscriber numbers

Individual subscriber numbers are $q_i \geq 0$ with market total $Q = \sum_{i=1}^{n} q_i$, and market shares are $s_i = q_i / Q$. Total penetration of the market is $\rho = Q / (N_c + N_e) \leq 1$. Subscribers of network i receive a gross utility of $w_i = S_i - f_i$, where S_i is the surplus from being connected to network i (a vertical differentiation parameter derived from quality and brand image), and f_i is the monthly subscription fee. The S_i must be large enough so that all competitive consumers subscribe, and their level also matters for adhesion of the captive segment.

We assume throughout that no competitive line ij is cornered by one of the networks, thus the indifferent consumer on line ij is located in its interior, at a distance x_{ij} from network i defined by

$$S_i - f_i - t_{ij}x_{ij} = S_j - f_j - t_{ij}(l - x_{ij}).$$

Solving for x_{ij} yields network i 's part of segment ij as

$$x_{ij} = \frac{l}{2} + \frac{1}{2t_{ij}}\left(S_i - f_i - S_j + f_j\right).$$

On the other hand, on each captive segment consumers at distance y from network i subscribe while $S_i - f_i - \tau_i y \geq 0$, i.e. we normalize the value of the outside option of captive consumers to zero. The indifferent elastic consumer is at

$$y_i = \frac{1}{\tau_i}\left(S_i - f_i\right).$$

Defining $\sigma_{ij} \equiv 1/2t_{ij} = \sigma_{ji}$, $\lambda_i = 1/\tau_i$ (with λ the corresponding ($n \times 1$)-vector and $\Lambda = diag(\lambda_i)$) and summing subscribers over segments yields network i 's subscriber number

$$q_i = \sum_{j \neq i} x_{ij} + y_i = \frac{N_c}{n} + \sum_{j \neq i} \sigma_{ij}\left(S_i - f_i - S_j + f_j\right) + \lambda_i\left(S_i - f_i\right).$$

With $\partial q_i / \partial f_i = -\left(\sum_{j \neq i} \sigma_{ij} + \lambda_i\right)$ and $\partial q_i / \partial f_j = \sigma_{ij}$, network i 's own- and cross-elasticities of demand are

$$\varepsilon_{ii} = -\frac{f_i}{q_i}\left(\sum_{j \neq i} \sigma_{ij} + \lambda_i\right), \varepsilon_{ij} = \frac{f_j}{q_i}\sigma_{ij}.$$

Let E be the $(n \times 1)$ vector of ones and $\boldsymbol{I}$ the $(n \times n)$ identity matrix. Let X be an $(n \times n)$ matrix with the values $X_{ii} = \sum_{j \neq i} \sigma_{ij} + \lambda_i$ and $X_{ij} = 0$ for $j \neq i$, and Y an $(n \times n)$ matrix with the values $Y_{ii} = \sum_{j \neq i} \sigma_{ij} + \lambda_i$ and $Y_{ij} = -\sigma_{ij}$ for $j \neq i$ ($E'Y = \lambda'$, $YE = \lambda$). Let S, f, q be the $(n \times 1)$ vectors of S_i , f_i , q_i . Then

$$q = \frac{N_c}{n} E + Y(S - f) = q_0 - Yf,$$

where q_0 is the vector of demands at zero subscription fees. Total demand is $Q(f) = E'q = N_c + \lambda'(S - f)$, with market demand elasticity (let $f = \bar{f}E$)

$$\eta = -\frac{\bar{f}\sum_{i=1}^{n}\lambda_i}{Q(\bar{f}E)}.$$

Consumer surplus is:

$$CS = q'(S - f) + \sum_{i=1}^{n}\left(\sum_{j \neq i}\int_0^{x_{ij}} t_{ij} x dx + \int_0^{y_i} \tau_i y dy\right)$$
$$= q'(S - f) + \sum_{i=1}^{n}\left(\sum_{j \neq i}\frac{x_{ij}^2}{4\sigma_{ij}} + \frac{y_i^2}{2\lambda_i}\right)$$

Costs, access and profits

Networks have fixed retail cost K_i (which can include annualized backbone investment cost for entrants) and variable per subscription cost of $C_i(q) = c_i q + d_i q^2 / 2$ (where $d_i = 0$ with constant returns in the variable part). Let c be the $(n \times 1)$-vector of c_i and $D = diag(d_i)$. Wholesale cost of the infrastructure are a fixed cost K_0 and variable cost $C_0(q) = c_0 q$.

The infrastructure is owned by a subset of $m \leq n$ networks, and network i obtains a share $\gamma_i \geq 0$ of the access profits, $\sum_{i=1}^{n}\gamma_i = 1$, and let $\Gamma = diag(\{\gamma_i\})$. If there is a vertically integrated incumbent $i = 1$ then $m = 1$ and $\gamma_1 = 1$, $\gamma_i = 0$ for $i > 1$. Access is charged according to a two-part tariff $A + aq$, where $A = 0$ if the tariff is linear. All networks pay this access price to the infrastructure owner(s) (for the latter access payments and receipts for own customers cancel out). Network i 's profits are

$$\pi_i = (f_i - a)q_i - C_i(q_i) - K_i - A + \gamma_i[(a - c_0)Q(f) - K_0 + nA]$$

The first terms correspond to retail profits after access cost, while the bracket on the right captures the respective share of wholesale profits (which may be zero).

Total welfare then consists of

$$W = CS + \sum_{i=1}^{n}\pi_i.$$

Equilibrium fees

Noting that $\partial Q(f)/\partial f_i = -\lambda_i$ (i.e. each network's fee only affects total demand through its own Hinterland) each network's FOC for profit-maximization becomes

$$\frac{\partial \pi_i}{\partial f_i} = q_i - \left(\sum_{j \neq i} \sigma_{ij} + \lambda_i \right) (f_i - c_i - d_i q_i - a) - \gamma_i \lambda_i (a - c_0) = 0.$$

Necessary SOCs are

$$\frac{\partial^2 \pi_i}{\partial f_i^2} = -2 \left(\sum_{j \neq i} \sigma_{ij} + \lambda_i \right) - d_i \left(\sum_{j \neq i} \sigma_{ij} + \lambda_i \right)^2 \leq 0,$$

which are satisfied as long as $d_i \geq -2/\left(\sum_{j \neq i} \sigma_{ij} + \lambda_i\right)$. Stacking the first-order conditions leads to:

$$q - X(f - c - Dq - aE) - (a - c_0)\Gamma\lambda = 0.$$

Solving for f leads to equilibrium fees

$$f^* = (X + Y + XDY)^{-1}\left[(I + XD)q_0 + X(c + aE) - (a - c_0)\Gamma\lambda\right].$$

With constant returns to scale ($D = 0$) we obtain

$$f^* = (X + Y)^{-1}\left[q_0 + X(c + aE) - (a - c_0)\Gamma\lambda\right].$$

The dependence of $X + Y$ on λ in the first bracket implies that having backyards leads to lower fees, as one should expect. The last term on the right-hand side translates the infrastructure owners' incentives to keep fees low and total demand high.

For the purpose of comparison with the traditional Hotelling model, consider also constant returns to scale and no backyards, i.e. $D = 0$ and $\lambda = 0$, together with $\sigma_{ij} \equiv \sigma$ for all $j \neq i$. Using that $\left[(2n-1)I - EE^T\right]^{-1} = \frac{1}{2n-1}\left(I + \frac{1}{n-1}EE^T\right)$, we find the equilibrium fees

$$f^* = \frac{N_c}{\sigma n(n-1)}E + c + aE + \frac{1}{2n-1}Y(S - c).$$

The terms in the latter expression are the following which we know from standard Hotelling models: 1. Returns due to local market power; 2. Individual marginal cost; 3. Costs common to all providers (here access cost); 4. Surcharges due to relative surplus (quality minus cost). It is known that with inelastic demand ($\Lambda = 0$) access charges just drive up the subscription fee, and so here they do.

Endogenizing the access charge

Since all firms in this model use access to the FTTH infrastructure, the LRIC access charge is

$$a = c_0 + K_0 / (E'q(a)),$$

where $q(a)$ is the vector of quantities as a function of the access charge a. We obtain the access demand function

$$\begin{aligned} E'q(a) &= E'q_0 - E'Yf^* \\ &= E'\left[q_0 - Y(X + Y + XDY)^{-1}((I + XD)q_0 + X(c + c_0 E))\right] \\ &\quad -\left[E'Y(X + Y + XDY)^{-1}(XE - \Gamma\lambda)\right](a - c_0) \\ &= b_0 - b_1(a - c_0), \end{aligned}$$

where $b_0 > 0$ is the equilibrium access quantity with access price equal to marginal cost, and $b_1 > 0$ indicates how access prices above marginal cost reduce access demand. Letting $\mu = a - c_0 > 0$ be the access margin, access revenue is $\mu(b_0 - b_1\mu)$, with maximum at $\tilde{\mu} = b_0 / 2b_1$. The condition defining the LRIC access charge is then

$$\mu(b_0 - b_1\mu) = K_0,$$

which, in the interval $[0, \tilde{\mu}]$, has the unique solution

$$\mu^* = \frac{b_0 - \sqrt{b_0^2 - 4b_1K_0}}{2b_1}.$$

No-Hinterland model

Consumers

There are N_c consumers who opt between pairs of firms (retailers). There are $n \geq 2$ firms, each at one of the n nodes of a complete graph of size N_c which describes competitive consumers' space of preferences over which they are uniformly distributed. The distance between two nodes is $l = 2N_c / n(n-1)$. All consumers subscribe to some firm. Horizontal differentiation is modelled in Hotelling fashion through a linear transport cost td , where $t > 0$ and d is the distance between the subscriber and his firm. Higher t is interpreted as originating from more horizontal differentiation due to more varied offers by firms or different technologies. Below we will let transport cost differ between pairs of firms, with $t_{ij} = t_{ji} > 0$.

Subscriber numbers

Individual subscriber numbers are $q_i \geq 0$ with market total $Q = \sum_{i=1}^{n} q_i$, and market shares are $s_i = q_i / Q$. Subscribers of firm i receive a gross utility of $w_i = S_i - f_i$, where S_i is the surplus from being connected to firm i (a vertical differentiation parameter derived from quality and brand image), and f_i is the monthly subscription fee. The S_i must be large enough so that all competitive consumers subscribe, and their level also matters for adhesion of the elastic segment.

We assume throughout that no competitive line ij is cornered by one of the firms, thus the indifferent consumer on line ij is located in its interior, at a distance x_{ij} from firm i defined by

$$S_i - f_i - t_{ij} x_{ij} = S_j - f_j - t_{ij}(l - x_{ij}).$$

Solving for x_{ij} yields firm i 's part of segment ij as

$$x_{ij} = \frac{l}{2} + \frac{1}{2t_{ij}}\left(S_i - f_i - S_j + f_j\right).$$

Defining $\sigma_{ij} \equiv 1/2t_{ij} = \sigma_{ji}$ and summing subscribers over segments yields firm i 's subscriber number

$$q_i = \sum_{j \neq i} x_{ij} = \frac{N_c}{n} + \sum_{j \neq i} \sigma_{ij}\left(S_i - f_i - S_j + f_j\right).$$

With $\partial q_i / \partial f_i = -\sum_{j \neq i} \sigma_{ij}$ and $\partial q_i / \partial f_j = \sigma_{ij}$, firm i 's own- and cross-elasticities of demand are

$$\varepsilon_{ii} = -\frac{f_i}{q_i} \sum_{j \neq i} \sigma_{ij}, \varepsilon_{ij} = \frac{f_j}{q_i} \sigma_{ij}.$$

Let E be the $(n \times 1)$ vector of ones and I the $(n \times n)$ identity matrix. Let X be an $(n \times n)$ matrix with the values $X_{ii} = \sum_{j \neq i} \sigma_{ij}$ and $X_{ij} = 0$ for $j \neq i$, and Y an $(n \times n)$ matrix with the values $Y_{ii} = \sum_{j \neq i} \sigma_{ij}$ and $Y_{ij} = -\sigma_{ij}$ for $j \neq i$ ($E'Y = 0$, $YE = 0$). Let S, f, q be the $(n \times 1)$ vectors of S_i , f_i , q_i . Then

$$q = \frac{N_c}{n} E + Y(S - f) = q_0 - Yf,$$

where q_0 is the vector of demands at zero subscription fees. Total demand is $Q(f) = E'q = N_c$.

Consumer surplus is:

$$\begin{aligned} CS &= q'(S - f) + \sum_{i=1}^{n} \sum_{j \neq i} \int_0^{x_{ij}} t_{ij} x dx \\ &= q'(S - f) + \sum_{i=1}^{n} \sum_{j \neq i} \frac{x_{ij}^2}{4\sigma_{ij}} \end{aligned}$$

Costs, access and profits

Firms have fixed downstream cost K_i and variable per subscription cost of $C_i(q) = c_i q + d_i q^2 / 2$ (where $d_i = 0$ with constant returns in the variable part). Let c be the $(n \times 1)$-vector of c_i and $D = diag(\{d_i\})$. These downstream costs are assumed to contain any infrastructure-related cost not attributable to the wholesale FTTH infrastructure. Wholesale cost of the FTTH infrastructure are a fixed cost K_0 and variable cost $C_0(q) = c_0 q$.

The FTTH infrastructure is owned by a subset of $m \leq n$ firms, and firm i obtains a share $\gamma_i \geq 0$ of the access profits, $\sum_{i=1}^{n} \gamma_i = 1$, with $\Gamma = diag(\{\gamma_i\})$. If there is a vertically integrated incumbent $i = 1$ then $m = 1$ and $\gamma_1 = 1$, $\gamma_i = 0$ for $i > 1$. Access is charged according to a two-part tariff $A + aq$, where $A = 0$ if the tariff is linear. Let

$\delta_i = 1$ for any firm that uses the FTTH infrastructure, and $\delta_i = 0$ for any firm that does not (e.g. cable operators), with δ the vector of the δ_i. If $\delta_i = 1$ then firm i pays for access price to the infrastructure owner(s) (for the latter access payments and receipts for own customers cancel out). Network i 's profits are

$$\pi_i = (f_i - a\delta_i)q_i - C_i(q_i) - K_i - A\delta_i + \gamma_i[\delta'((a - c_0)q + AE) - K_0].$$

The first terms correspond to retail profits after access payments, while the bracket on the right captures the respective share of wholesale profits (which may be zero).

Total welfare is the sum of consumer surplus and profits:

$$W = CS + \sum_{i=1}^{n} \pi_i.$$

Equilibrium fees

We have

$$\frac{\partial(\delta' q)}{\partial f_i} = \sum_{j=1}^{n} \delta_j \frac{\partial q_j}{\partial f_i} = -\delta_i \sum_{j \neq i} \sigma_{ij} + \sum_{j \neq i} \delta_j \sigma_{ji}.$$

Each firm's FOC for profit-maximization becomes

$$\frac{\partial \pi_i}{\partial f_i} = q_i - (f_i - c_i - d_i q_i - a\delta_i)\sum_{j \neq i} \sigma_{ij} - (a - c_0)\gamma_i \left(\delta_i \sum_{j \neq i} \sigma_{ij} - \sum_{j \neq i} \delta_j \sigma_{ij} \right) = 0.$$

Necessary SOCs are

$$\frac{\partial^2 \pi_i}{\partial f_i^2} = -2\sum_{j \neq i} \sigma_{ij} - d_i \left(\sum_{j \neq i} \sigma_{ij} \right)^2 \leq 0,$$

which are satisfied as long as $d_i \geq -2 / \sum_{j \neq i} \sigma_{ij}$. Stacking the first-order conditions leads to:

$$q - X(f - c - Dq - a\delta) - (a - c_0)\Gamma Y\delta = 0.$$

Solving for f leads to equilibrium fees

$$f^* = (X + Y + XDY)^{-1}[(I + XD)q_0 + X(c + a\delta) - (a - c_0)\Gamma Y\delta].$$

With constant returns to scale ($D = 0$) we obtain

$$f^* = (X + Y)^{-1}\left[q_0 + X(c + a\delta) - (a - c_0)\Gamma Y\delta\right].$$

The last term on the right-hand side translates the infrastructure owners' incentives to keep fees low and demand of retail services based on their infrastructure high.

Endogenizing the access charge

Assuming that firm 2 is a cable company that does not use access to the FTTH infrastructure, we have $\delta = E - e_2$, and the LRIC access charge is

$$a = c_0 + K_0 / (N - q_2(a)) = c_0 + K_0 / (\delta' q(a)),$$

where $q(a)$ is the vector of quantities as a function of the access charge a . We obtain the access demand function

$$\begin{aligned} \delta' q(a) &= \delta' q_0 - \delta' Y f^* \\ &= \delta'\left[q_0 - Y(X + Y + XDY)^{-1}\left((I + XD)q_0 + X(c + c_0\delta)\right)\right] \\ &\quad -\left[\delta' Y(X + Y + XDY)^{-1}(X - \Gamma Y)\delta\right](a - c_0) \\ &= b_0 - b_1(a - c_0), \end{aligned}$$

where $b_0 > 0$ is the equilibrium access quantity with access price equal to marginal cost, and $b_1 > 0$ indicates how access prices above marginal cost reduce access demand. Letting $\mu = a - c_0 > 0$ be the access margin, access revenue is $\mu(b_0 - b_1\mu)$, with maximum at $\tilde{\mu} = b_0 / 2b_1$. The condition defining the LRIC access charge is then

$$\mu(b_0 - b_1\mu) = K_0,$$

which, in the interval $[0, \tilde{\mu}]$, has the unique solution

$$\mu^* = \frac{b_0 - \sqrt{b_0^2 - 4b_1K_0}}{2b_1}.$$