Access Networks for Mobility

A Techno-Economic Model for Broadband Access Technologies

João Paulo Ribeiro Pereira
Instituto Politécnico de Bragança (IPB)
Bragança, Portugal
jprp@ipb.pt

Pedro Ferreira
Instituto Superior Técnico (IST)
Lisboa, Portugal
pedro.assis.ferreira@ist.utl.pt

Abstract— **The two main challenges for the access networks are the increasing bandwidth demand and mobility trends. The "triple play" services required (Internet, telephone and TV services) lead to a great increase in bandwidth demand. However, the existing access networks are not able to support this increase, and the capacity to delivery broadband services remain as a challenge ("last mile problem"). The access network remains a bottleneck in terms of the bandwidth and service quality it affords the end user. Besides the bandwidth, other great challenge to access networks is the mobility and the user need to have internet access anywhere and anytime. Then, the increasing demand of "quad-play" (also known as quadruple-play) services, including video, voice, data and mobility, have created new challenges to the modern broadband wireless/wired access networks. This document proposes a techno-economic model to support the new requirements of fixed and nomadic users.**

Access Networks, Broadband Access Technologies, Techno-economic cost model

I. INTRODUCTION

The requirements for bandwidth capacity have increased significantly over the last several years. The requirements for services such as HDTV, video conferences, peer-to-peer traffic, etc., have led to predictions of bandwidth consumption of at least 50Mbps downstream for residential consumers and in the region of 8 Mbps upstream [1]. The two main challenges for the access networks are the increasing bandwidth demand and mobility trends. The "triple play" services (Internet, telephone and TV services), lead to a great increase in bandwidth demand. However, the existing access networks are not able to support this increase and the capacity to deliver broadband services remains a challenge ("last mile problem"). The access network remains a bottleneck in terms of the bandwidth and service quality it affords the end user. Besides the bandwidth, other great challenge to access networks is the mobility and the user needs to have internet access anywhere and anytime. The mobility of the end-user will also introduce an unprecedented volatility to the network architecture [2;3]. Nomadicity causes end-users to pop up and disappear at different locations in the network. All this will require fundamental changes to the operations of access networks, the functionality of network nodes, and the architecture itself.

Then, the increasing demand of "quad-play" (also known as quadruple-play) services, including video, voice, data and mobility, have created new challenges to the modern broadband wireless/wired access networks.

II. TECHNO-ECONOMIC MODEL FOR MOBILITY

The proposed model considers that in the static layer, users are stationary and normally require data, voice, and video quality services (these subscribers demand great bandwidth). In the nomadic layer (or mobility layer), the main concern is mobility and normally the required bandwidth is smaller than in the static layer. The focus of the wireless networks was to support mobility and flexibility, while for the wired access networks is bandwidth and high QoS. However, with the advances in technology, wireless solutions such as WiMAX have capacity to provide wideband and high QoS services and in this way competing with wired technologies [4]. Then, we propose a new model to support the new needs of the access networks: bandwidth and mobility (see Figure 1)
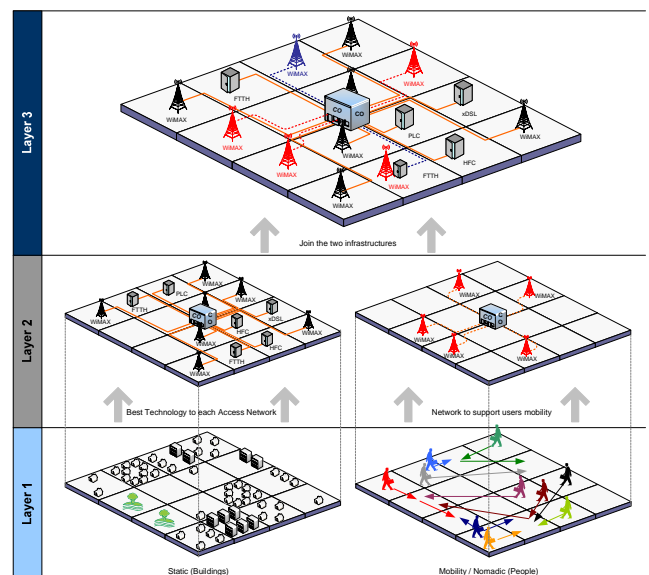

Figure 1. Cost model framework

For the nomadic layer we chose the WiMAX solutions. This technology enables long distance wireless connections with speeds up to 75 Mbps per second. WiMAX can be used for a number of applications, including "last mile" broadband

connections, hotspot and cellular backhaul and high-speed enterprise connectivity for businesses. This technology can offer very high data rates and extended coverage [5;6].

The proposed model divides the area into several access networks (Figure 1 is divided into 16 sub-areas, but the main area can be divided between 1 and 36 sub-areas). The central office (CO) is located in the center of the area, and each sub-area will have one or more aggregation nodes (AGN) depending on the technology in use. However, if a particular sub-area doesn't have homes, SMEs or nomadic users, the model will not consider any AGN or trench.

As we can see in Figure 1, the framework is divided into three main layers: (Layer 1) First, we identify for each sub-area the total households and SMEs (Static analysis), and total nomadic users (Mobility analysis). The proposed model initially separates these two components because they have different characteristics. (Layer 2) In this layer, the best solution for each access network is analyzed (static and nomadic perspective). For the static analysis we consider Fiber to the Home (FTTH- PON), Digital Subscriber Line (DSL), Hybrid Fiber Coax (HFC), Power Line Communications (PLC) and WiMAX technologies, and for the nomadic analysis we use the WiMAX technology. Then, the final result of this layer is the best technological solution to support the different needs (Static and nomadic). The selection of the best option is based in four output results: NPV, IRR, Cost per subscriber in year 1, and Cost per subscriber in year n. (Layer 3) The next step is the construction of a single infrastructure that supports the two components. To this end, the tool analyses for each access network which is the best solution (based on NPV, IRR, etc). Finally, for each sub-area we verify if the best solution is: a) The wired technologies (FTTH, DSL, HFC, and PLC) to support the static component and the WiMAX technology for mobility; or b) The use of WiMAX technology to support the fixed and nomadic component.

A. Access Network Architecture

The model focuses the access part of the network, starts at CO and end at the subscriber CPE. The cost model is based on a single CO (centralized), connecting the subscribers through several aggregation nodes. The goal is to optimize the network in order to minimize the costs for a given performance criterion [7].

The outside segment is divided into three main parts (see Figure 2) [8]: Feeder, Aggregation Nodes and Distribution (for HFC technology the distribution segment is divided into distribution and drop). Feeder segment is the network between the CO and the aggregation nodes. The model includes not only the cost of equipment (Fiber repeaters), but also the optical fiber cables, installation, trenches, and housing (street cabinets) costs. The ducts can be shared by several optical fiber cables. The aggregation nodes are located in access areas street cabinets. The components of these nodes depend on the technology. In the next paragraphs we will present the elements for the five technologies in study. The distribution network links the aggregation nodes with CPE. Like feeder networks, in distribution, the model includes not only the cost of equipment

(copper, coax, and LV grid repeaters), but also the cables, installation and trenches costs.
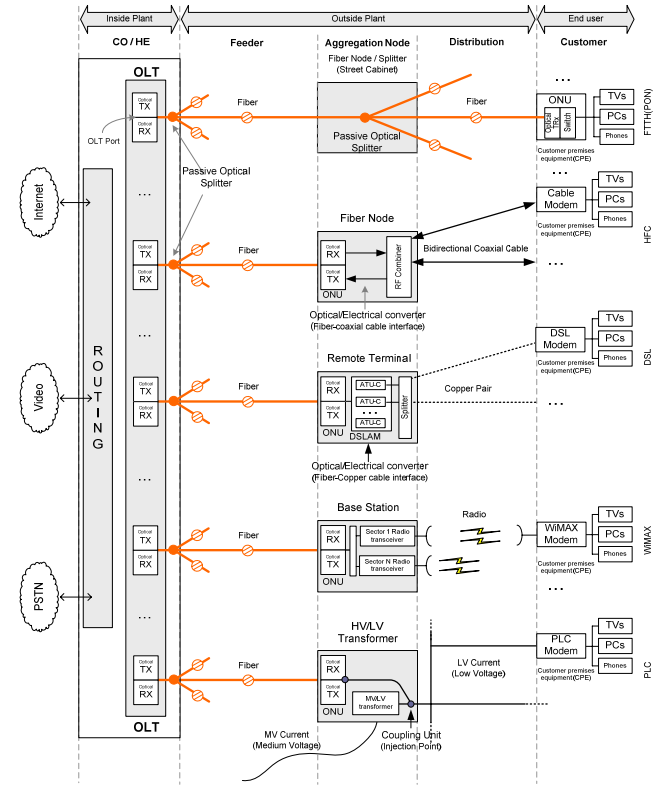

Figure 2. Block diagram for Access Technologies

The Capital Expenses (CAPEX) costs referred above are divided into: equipment costs, installation costs, cable costs, housing costs and civil works. Besides the annual capital costs, which are derived from the relevant values for directly and indirectly attributable investments, other costs also need to be taken into account, for instance those incurred for the network's operation and maintenance (OPEX -Operational Expenses).

Next tables show the components used for the five segments described in Figure 2: Inside plant; Feeder; Aggregation Node; Distribution; and End user. Table one shows the components for the inside plant and feeder segment. These components are common for all the technologies.

TABLE I. INSIDE AND FEEDER NETWORK SEGMENT

Inside Plant	Outside Plant
	FEEDER
1) OLT ports	1) Optical repeater
2) Chassis	2) Repeater installation
3) Splitter (Primary Split)	3) Aerial/Buried trenches/ducts (Trenching costs)
3) Installation: Ports, chassis, and split.	4) Fiber Cable (cable cost)
	5) Cable Installation

The aggregation node, distribution network, and end user components are different for each technology. The following tables (Table 2, 3, 4, 5, and 6) show the components used for the several technologies.

TABLE II. FTTH(PON) ARCHITECTURE COMPONENTS

Outside Plant		End User
AGN	DISTRIBUTION	
1) Splitter (Secondary Split) 2) Splitter Installation 3) Housing: Street Cabinet	1) Optical repeater 2) Repeater installation 3) Aerial/Buried trenches/ducts (Trenching costs) 4) Fiber Cable (cable cost) 5) Cable Installation	1) ONU 2) Fiber Modem 2) Installation

TABLE III. WiMAX ARCHITECTURE COMPONENTS

Outside Plant		End User
AGN	DISTRIBUTION	
1) Site acquisition 2) Site lease 3) Civil works BS/Cabinets 4) Housing Cabinet / Closures for each BS 5) PMP equipment (multiplexer + cost sector X # sectors per BS) 6) BS installation Cost (including sectors) 7) ONU (BS) and Installation	(Wireless PMP Access)	1) WiMAX terminal (include: Antenna, Transceiver, Radio Modem) 2) Installation

TABLE IV. DSL ARCHITECTURE COMPONENTS

Outside Plant		End User
AGN	DISTRIBUTION	
1) Node Cabinet equipment: - ONU - DSLAM - Line-cards - Splitter - Chassis - Racks 2) Equipment Installation 3) Housing: Street Cabinet	1) Copper regenerator / repeater 2) Repeater installation 3) Aerial/Buried trenches (Trenching costs) 4) Copper Cable (cable cost) 5) Cable Installation	1) xDSL Modem 2) Splitter 3) Installation

TABLE V. HFC ARCHITECTURE COMPONENTS

Outside Plant		End User
AGN	DISTRIBUTION	
1) Fiber Node Cabinet equipment: - O/E converter (ONU) - RF combiner 2) Equipment Installation 3) Housing: Street Cabinet	1) RF amplifier 2) Amplifier installation 3) Aerial/Buried trenches (Trenching costs) 4) Coaxial Cable (cable cost) 5) Cable Installation	1) Cable Modem 2) Splitter 2) Installation

TABLE VI. PLC ARCHITECTURE COMPONENTS

Outside Plant		End User
AGN	DISTRIBUTION	
1) Local MV/LV Transformer Station equipment (TE equipment): - O/E converter (The O/E device at a pole or Ground) - Coupling unit (injection point) 2) Equipment Installation 3) Housing: Street Cabinet	1) Repeater for LV network 2) Installation	1) PLC Modem 2) Installation

B. Geometric Model Assumptions

The geometrical model definition is required to calculate the length of trenches, ducts and cables. Some of the construction techniques are: Aerial: string along utility poles (mostly rural areas); Trench: dig up earth and lay new conduit and fiber (used in urban areas); and Pull-through: run through existing underground conduits. As each technology has different characteristics, the model has different assumptions for the several access technologies, which are described in the previous sections.

In our work we consider that trench length represents the required civil work for digging and ducting – The model doesn't distinguish between aerial (overhead poles) and buried (underground ducts). However, the costs are higher when the infrastructure is buried than when it can be installed on existing poles (normally, aerial installation is almost twice inexpensive as when the infrastructure is buried).

1) Calculating the lengths of the Feeder Networks

As we can see above, the cost model is based on a single centralized CO, connecting the subscribers through several aggregation nodes. The geographical area is divided into squares and each grid square represents a distribution area (access area) (see Figure 3). Each access area could have different demographic characteristics.
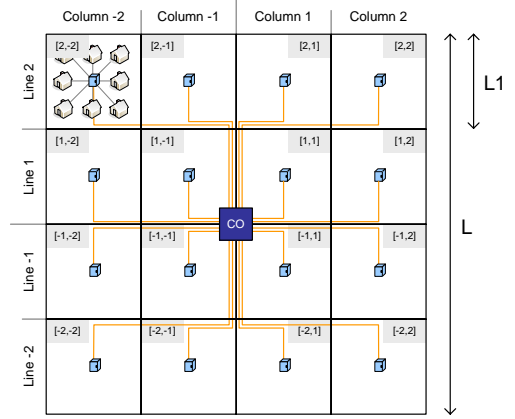
Figure 3. Geometric model for Feeder Networks

To calculate the total distance for the feeder networks (network between CO and Fiber Node) we use the following formulas:

Calculating the lengths of the Feeder Network for all Access Areas (1):

$$TotalLength_{FeederNetwork} = \left(\frac{\sqrt{TotalAccessAreas}}{2} \right) * L1 \tag{1}$$

Calculating the lengths of the Feeder Network for each Access Area (2):

$$FeederNetworkLength_{Celli} = ((Line_i - Column_i) - 1 * L1 \tag{2}$$

Where:

$$L1 = \sqrt{\frac{Total\_Area}{TotalAccessArea}}$$

The number of required fibers to connect each aggregation node to the CO depends on the technology that is used in the access network area. For example, for FTTH (PON) we use the following formula (3):

$$Fibers_{AGN\_i} = \left(\frac{TotSubs_{Area\_i}}{SecondarySplitRatio} \right). \tag{3}$$

2) Calculating the lengths of the Distribution Networks

The access areas can be divided into five circular areas (between 1 and 5). This way, we can distribute the users in each access area, and calculate the trenches and required cable for the wired technologies (Figure 4). For the wireless technologies, this structure is a good option to make a better management of the required base stations for each access area.

For the distribution segment, it is assumed that subscribers are connected to an aggregation node by a single wire (fiber, twisted par, or coax wire) or none (for wireless technologies). Then, each subscriber is connected through a dedicated medium to the aggregation node located in the center of the square area.
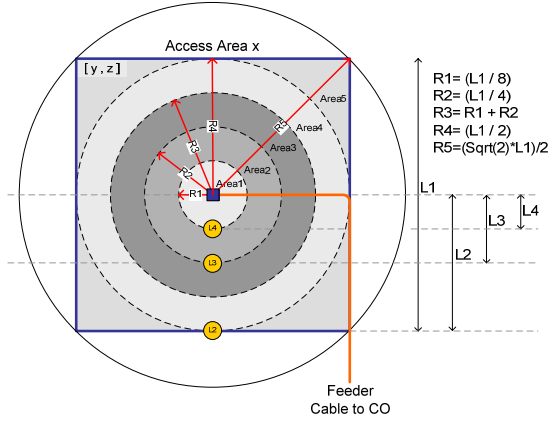

Figure 4. Geometric model for Distribution Networks

To compute the lengths of the Distribution Network for each access area we use the formula (4):

$$DNL_{Celli} = (R_{Area1} + TotSubsc_{Area1}) + (R_{Area2} + TotSubsc_{Area2}) + \\ (R_{Area3} + TotSubsc_{Area3}) + (R_{Area4} + TotSubsc_{Area4}) + (R_{Area5} + TotSubsc_{Area5}) \quad (4)$$

Where: DNL= Distribution Network; R_{Area}= Radius Area; and TotSubsc$_{Area}$= Total subscribers

III. RESULTS

A. Scenario description

The three main activities for scenario description are: area definition, definition of the set of services to be offered, and the pricing (see Table 7). Table 7 shows the general input parameters used in our model and tool. The trends for each parameter are presented in the last column. This scenario is defined for a study period of 15 years and for an urban area. The definition of the area type is essential because several costs between urban and rural areas are different.

After the general specification, is obligatory the definition of the number of access networks in which we want to divide the area in study is compulsory (between 1 and 36) (see Figure 8). This scenario assumes the division into 4 sub-areas (or access networks).

TABLE VII. GENERAL INPUT PARAMETERS DESCRIPTION

		Value	Trend (% per year)
		Scenario	
Years (Study Period)		15	
Geographical Area Description		Urban	
Area Characteristics	Area Size (Km2)	25	0,00%
	Residential		
	Total Households (potential subscribers)	7100	2,00%
	Households Density (Households / Km2)	**284**	
	Population Density (people/Km2)	1200	3,80%
	Population	**30.000**	
	Inhabitants per household	**4,23**	
	Technology penetration rate (expected market penetration)	50,00%	8,00%
	Number of subscribers	**3.550**	
	Average Households per building	14	
	Number of buildings in serving area (homes/km2)	**507**	
	SME (small-to-medium sized enterprises)		
	Total SME in Area	1050	2,00%
	Technology penetration rate (expected market penetration)	40,00%	5,00%
	Total SME (customers)	**420**	
	Nomadic Users		
	Total Nomadic Users	1500	15,00%
Service Characteristics	**Residential**		
	Required Downstream bandwidth (Mbps): Avg data rate	10	1,2%
	Required Upstream bandwidth (Mbps): Avg data rate	0,512	1,2%
	SME		
	Required Downstream bandwidth (Mbps): Avg data rate	12	1,2%
	Required Upstream bandwidth (Mbps): Avg data rate	0,512	1,2%
	Nomadic Users		
	Required Downstream bandwidth (Mbps): Avg data rate	2	2,0%
	Required Upstream bandwidth (Mbps): Avg data rate	0,512	2,0%
Pricing	**Residential**		
	One-time Activation/connection fee (€)	100	0,15%
	Subscription fee (€ / month)	50	0,15%
	SME		
	One-time Activation/connection fee (€)	150	0,15%
	Subscription fee (€ / month)	75	0,15%
	Nomadic Users		
	One-time Activation/connection fee (€)	75	0,15%
	Subscription fee (€ / month)	45	0,15%
Discount Rate (on cash flows)		0%	

Following, the definition of the number of households (HH), SMEs and nomadic users is also required, for each access network (see Table 8).

TABLE VIII. INPUT PARAMETERS FOR EACH ACCESS NETWORK

Grid (Total Access Networks)	**4**
Area (km2)	**25**
S (Km): sqrt(Total area)	**5,00**
Access Network area (Km2)	**6,25**
S (Km): sqrt(Access Network area)	**2,50**

Year1	
Total HH:	**7100**
Total SME:	**1050**
Total Nomadic Users:	**1500**

	1	2
HH:	6000	0
SME:	1000	0
Nomadic Users:	500	0
	3	**4**
HH:	0	1100
SME:	0	50
Nomadic Users:	1000	0

1) Feeder network parameters

As defined in previous sections, the technology used for the feeder network is the FTTH(PON). Fiber is clearly the preferred choice for digital backbone network because of its unrivalled bandwidth capacity. Fiber offers enormous

bandwidth in both directions and so effectively eliminates the issue of symmetry, which is a limitation of other platforms such as DSL, cable, etc.[3;9].

We assume that the primary splits are located at the CO. Table 9 shows the feeder network parameters assumed in our study. To calculate the trench and cable lengths we use the geometrical model assumptions previously described.

TABLE IX.   FEEDER NETWORK PARAMETERS

Technology	
Primary Split (located at CO)	04
OLT Chassis	
Number of OLT card slots per OLT Chassis	16
OLT Cards (only for Subs not for HP)	
Number of OLT ports per Card	08
Max. ONU's per OLT Port	64
Downstream Rate (Mbps) per OLT port	622
Upstream Rate (Mbps) per OLT port	155
Optical repeater and Copper regenerator	
Distance between Optical Repeater (km)	30
Trench Parameters	
Total Trench Lenght (Km)	**7,50**
% of new trenches	65%
Street Cabinet Parameters	
Total Street Cabinets	
% of new Street Cabinets/Closures	60%
Max. Number of Users per Street Cabinet(AGN)	FNodeCab_2048user
Cable Parameters for feeder network	
% of new cable	60%
Cable type	OpticalCable48Fiber
Capacity per fiber (Gb/s)	1

For parameter "% of new trenches", 100% assumes that there isn`t any trench (Greenfield). The same way, for "% of new cable", 0% assumes the existence of an optical fiber infrastructure.

2) Distribution network parameters

The distribution networks are divided into 5 circular areas and to each of these areas, the radius is calculated as described in the previous section (Figure 4). For example, to DSL technology it is necessary to know the distance to choose which technology we must use (ADSL or VDSL). For the WiMAX technology, the radius of the areas is fundamental to calculate the base stations required to cover the area. Table 10 shows the specific parameters to several technologies.

TABLE X.   DISTRIBUTION NETWORK PARAMETERS: TECHNOLOGY PARAMETERS

Technology	
FTTH(PON)	
Secondary Split (Street Cabinet)	**08**
Split Ratio: Subsc per OLT port	**32**
xDSL	
xDSL tecnhnoloy	**VDSL**
ONU	
Maximum DS Capacity per ONU (Mbps)	**2000**
Maximum US Capacity per ONU (Mbps)	**1000**
Remote Terminal DSLAM	
DSLAM Units (Chassis)	VDSL_DSLAM_Chassis_LineCard_6
Number of Line Cards (ATU-Cs) per DSLAM unit: Slots	**6**
DSLAM Line Card (only for Subs not for homes passed)	VDSL_Line_card_ports_48
Number of port per line card (Max. subs per line card)	**48**
Downstream Rate (Mbps) per DSLAM line card port	**8,00**
Upstream Rate (Mbps) per DSLAM line card port	**2,00**
DSLAM Line Card Splitter	
DSLAM Splitter Card	VDSL_Line_card_Splitter_ports_48
Remote cabinet capacity	
Max. Number of DSLAMs per cabinet	**5**
Copper regenerator /repeater	
Distance Between Copper Repeater (km)	**5**

HFC	
ONU	
Maximum DS Capacity per ONU (Mbps)	**2000**
Maximum US Capacity per ONU (Mbps)	**1000**
Number of Ports per ONU (for RF modem)	**8**
RF node modem	
Maximum DS Capacity per RF Node Modem (Mbps)	**100**
Maximum US Capacity per RF Node Modem (Mbps)	**100**
RF amplifiers (2-way)	
Distance Between RF Amplifiers (2-way): km	**2**
TAP equipment	
Number of Drops per TAP	**2**
WiMAX	
ONU	
Maximum DS Capacity per ONU (Mbps)	**2000**
Maximum US Capacity per ONU (Mbps)	**1000**
Base Station	
Downstream Sector capacity (Mbps)	**36**
Upstream Sector capacity (Mbps)	**10**
Maximum sector throughput (Mbps): Capacity per sector	**46**
Maximum number of sectors per base station	**4**
Max. Base Station range - radius (km)	**3**
CPE (only for Subs not for homes passed)	
% of Indoor CPE	**60%**
% of Outdoor CPE	**40%**
PLC	
ONU	
Maximum DS Capacity per ONU (Mbps)	**2000**
Maximum US Capacity per ONU (Mbps)	**1000**
LV Transformer equipment	
Number of MV/LV transformers per Transformer Substation	**1**
AVG Number of feeders per MV/LV transformer	**8**
Downstream LV TE capacity (Mbps): for LV link between TE-CPEs	**25**
Upstream LV TE capacity (Mbps)	**25**
Max. Number HH per MV/LV transformer: # Customers per LV network	**20**
PLC Repeater for all LV networks (all homes passed)	
AVG Length of the LV lines (m)	**0,3**
Maximum repeater reach (m)	**0,325**
Average number of repeaters in Single house	**0**
Average number of repeaters in building (repeater in the meter room)	**1,27**

The model uses the parameters presented in Table 11 to describe the passive infrastructure. Like feeder network, the value 100% in the "% of new trenches" parameter, assumes that there isn't exist any trench (Greenfield). The same way, for "% of new cable", 0% assumes the existence of a cable infrastructure.

TABLE XI.   DISTRIBUTION NETWORK PARAMETERS: INFRASTRUCTURE PARAMETERS

	FTTH(PON)	xDSL	HFC	PLC	WiMAX
CPE (only for Subs not for homes passed)					
% of CPE cost suported by the operator	100%	100%	100%	100%	100%
Trench Costs					
% of new trenches	10%	8%	10%		
% of new trenches: Drop			30%		
Housing Costs					
% of BS needing new sites (Site Acquisition)					90%
% of BS with annual site lease					50%
Cable Costs					
% of new cable	10%	2%	10%		
Cable type	Optical Cable 24 Fibers	CopperCable 24 Fibers	CoaxCable5	Low Voltage Cable	
% of new cable: Drop			20%		
Cable type: Drop			CoaxCable5		
Avg Drop Length (Km)			0,300		

Finally, the distribution of the HH and SME in the access networks is required too. Then, for each zone the localization of the users is defined.

3) Results

This section presents the summarized results for each access network. These are divided into three main categories: 1) Results for the static layer: results for the use of FTTH (PON), WiMAX, DSL, HFC, and PLC technologies to support the fixed users; 2) Results for the nomadic layer: Results for the use of WiMAX technology to support the nomadic users and; 3) Results for the use of WiMAX technology to support the fixed and nomadic users.

a) General results

Table 12 shows the results for the use of the several technologies to support the static layer (HH and SMEs). Each column corresponds to an access network. The output variables are represented in the lines: Payback period, NPV, IRR, Cost per subscriber in year 1, and cost per subscriber in year n.

TABLE XII.   ECONOMIC RESULTS FOR STATIC LAYER

		Access Network 1	Access Network 2	Access Network 3	Access Network 4
	# Fixed Users	7000	0	0	1150
FTTH	Payback Period	10	0	0	18
	NPV	28.286.155 €	- €	- €	- 32.821 €
	IRR	11,09%	0,00%	0,00%	-0,05%
	Cost Subc Y1	6.695 €	- €	- €	12.522 €
	Cost Subc Y15	158 €	- €	- €	217 €
	CAPEX	32.930.229 €	- €	- €	10.010.356 €
	OPEX	8.032.648 €	- €	- €	1.466.364 €
WIMAX	Payback Period	36	0	0	48
	NPV	- 10.444.706 €	- €	- €	- 2.133.829 €
	IRR	-8,25%	0,00%	0,00%	-10,51%
	Cost Subc Y1	6.003 €	- €	- €	6.121 €
	Cost Subc Y15	579 €	- €	- €	575 €
	CAPEX	62.715.519 €	- €	- €	10.726.701 €
	OPEX	16.978.219 €	- €	- €	2.851.027 €
DSL	Payback Period	13	0	0	31
	NPV	14.170.447 €	- €	- €	- 4.733.161 €
	IRR	4,37%	0,00%	0,00%	-6,13%
	Cost Subc Y1	9.756 €	- €	- €	18.448 €
	Cost Subc Y15	186 €	- €	- €	276 €
	CAPEX	46.666.236 €	- €	- €	14.579.929 €
	OPEX	8.412.348 €	- €	- €	1.597.132 €
HFC	Payback Period	11	0	0	19
	NPV	22.757.156 €	- €	- €	- 803.336 €
	IRR	7,89%	0,00%	0,00%	-1,21%
	Cost Subc Y1	8.031 €	- €	- €	13.651 €
	Cost Subc Y15	164 €	- €	- €	222 €
	CAPEX	38.340.215 €	- €	- €	10.766.746 €
	OPEX	8.151.660 €	- €	- €	1.480.490 €
PLC	Payback Period	14	0	0	33
	NPV	7.568.328 €	- €	- €	- 5.584.241 €
	IRR	2,28%	0,00%	0,00%	-6,96%
	Cost Subc Y1	10.566 €	- €	- €	19.658 €
	Cost Subc Y15	226 €	- €	- €	285 €
	CAPEX	52.021.361 €	- €	- €	15.101.370 €
	OPEX	9.659.342 €	- €	- €	1.926.771 €

Next table shows the results for the use of WiMAX technology to support the nomadic users (mobility layer).

TABLE XIII.   ECONOMIC RESULTS FOR WiMAX (NOMADIC LAYER)

		Access Network 1	Access Network 2	Access Network 3	Access Network 4
	# Nomadic Users	500	0	1000	0
WIMAX	Payback Period	4	0	4	0
	NPV	7.916.374 €	- €	14.730.995 €	- €
	IRR	58,28%	0,00%	51,51%	0,00%
	Cost Subc Y1	1.490 €	- €	1.592 €	- €
	Cost Subc Y15	195 €	- €	225 €	- €
	CAPEX	3.530.797 €	- €	8.120.711 €	- €
	OPEX	1.851.388 €	- €	3.745.412 €	- €

b) Choice of the Best Solution

In this section we explain the used methodology to find the best technological solution for each access network. As we have previously said, the choice of the solution is based on four output results: NPV, IRR, Cost per subscriber Y1, and cost per subscriber Yn. Then, the choice processes have two steps:

- To sum the results from static layer (Table 12) with the results from nomadic layer (Table 13). For example, the first table sums the results from FTTH (Fixed) with the results of WiMAX (Nomadic). We have five combinations of technologies: four combinations of the wired technologies (that support the static layer) with WiMAX technology (that support the nomadic layer), and the results for the use of WiMAX technology to support the fixed and nomadic users (WiMAX: Fixed and Nomadic).

- The second step is to find, for the four output variables, the maximum value (for NPV and IRR) and the minimum value (for the costs per subscriber) so that we can find the best solution (see Table 14).

TABLE XIV.   BEST SOLUTION FOR EACH ACCESS NETWORK

		Access Network 1	Access Network 2	Access Network 3	Access Network 4	Results
NPV	Best Solution	FTTH(Fixed) + WiMAX(Nomadic)	-	WiMAX	FTTH(Fixed) + WiMAX(Nomadic)	Results
	for Fixed Layer	FTTH	-	-	FTTH	
	for Nomadic Layer	WiMAX	-	WiMAX	-	
	NPV	36.202.528 €	- €	14.730.995 €	- 32.821 €	12.725.176 €
	IRR	69,37%	-	51,51%	-0,05%	40,28%
	Cost Subc Y1	8.185 €	-	1.592 €	12.522 €	7.433 €
	Cost Subc Y 15	353 €	-	225 €	217 €	265 €
	CAPEX	36.461.026 €	-	8.120.711 €	10.010.356 €	54.592.093 €
	OPEX	9.884.036 €	-	3.745.412 €	1.466.364 €	15.095.812 €
IRR	Best Solution	FTTH(Fixed) + WiMAX(Nomadic)	-	WiMAX	FTTH(Fixed) + WiMAX(Nomadic)	
	for Fixed Layer	FTTH	-	-	FTTH	
	for Nomadic Layer	WiMAX	-	WiMAX	-	
	NPV	36.202.528 €	-	14.730.995 €	32.821 €	16.966.901 €
	IRR	69,37%	0,00%	51,51%	-0,05%	30,21%
	Cost Subc Y1	8.185 €	-	1.592 €	12.522 €	7.433 €
	Cost Subc Y 15	353 €	-	225 €	217 €	265 €
	CAPEX	36.461.026 €	-	8.120.711 €	10.010.356 €	54.592.093 €
	OPEX	9.884.036 €	-	3.745.412 €	1.466.364 €	15.095.812 €
Cost Subscriber Y1	Best Solution	WIMAX (Fixed and/or Nomadic)	-	WiMAX	WIMAX (Fixed and/or Nomadic)	
	for Fixed Layer	WiMAX	-	-	WiMAX	
	for Nomadic Layer	WiMAX	-	WiMAX	-	
	NPV	- 3.091.192 €	-	14.730.995 €	- 2.196.948 €	3.147.618 €
	IRR	-1,85%	-	51,51%	-10,93%	12,91%
	Cost Subc Y1	5.421 €	- €	1.592 €	6.121 €	3.283 €
	Cost Subc Y 15	504 €	-	225 €	577 €	435 €
	CAPEX	66.788.723 €	-	8.120.711 €	10.787.696 €	85.697.130 €
	OPEX	18.850.058 €	-	3.745.412 €	2.853.152 €	25.448.622 €
Cost Subscriber YN	Best Solution	FTTH(Fixed) + WiMAX(Nomadic)	-	WiMAX	FTTH(Fixed) + WiMAX(Nomadic)	
	for Fixed Layer	FTTH	-	-	FTTH	
	for Nomadic Layer	WiMAX	-	WiMAX	-	
	NPV	36.202.528 €	-	14.730.995 €	- 32.821 €	16.966.901 €
	IRR	69,37%	-	51,51%	-0,05%	40,28%
	Cost Subc Y1	8.185 €	-	1.592 €	12.522 €	7.433 €
	Cost Subc Y 15	353 €	- €	225 €	217 €	199 €
	CAPEX	36.461.026 €	-	8.120.711 €	10.010.356 €	54.592.093 €
	OPEX	9.884.036 €	-	3.745.412 €	1.466.364 €	15.095.812 €

B. Sensitivity Analysis

For the sensitivity analysis we use tables and the tornado diagrams (graphical sensitivity analysis technique).

TABLE XV.   SENSITIVITY ANALYSIS FOR FTTH(PON) TECHNOLOGY

FTTH (PON)			CostPerSubscriber			
Parameters Names	Low Parameter Values	High Parameter Values	Output for Low Value		Output for High Value	
Base Value: 6695,21				%		%
TakeRateHH	-60%	60%	25.311 €	**278,0%**	4.037 €	**-39,7%**
CAPEX_Civil_Works	-50%	50%	3.774 €	**-43,6%**	9.616 €	**43,6%**
CoverageArea	-60%	60%	5.146 €	**-23,1%**	8.244 €	**23,1%**
PotentialHH	-60%	60%	7.891 €	**17,9%**	6.453 €	**-3,6%**
TakeRateSME	-60%	60%	7.378 €	**10,2%**	6.133 €	**-8,4%**
PotentialSMEs	-60%	60%	6.334 €	**-5,4%**	7.005 €	**4,6%**
CAPEX_Equipment	-50%	50%	6.549 €	**-2,2%**	6.841 €	**2,2%**
CAPEX_Cable	-55%	55%	6.601 €	**-1,4%**	6.790 €	**1,4%**
OPEX_Civil_Works	-50%	50%	6.608 €	**-1,3%**	6.783 €	**1,3%**
CAPEX_Installation(Equip)	-55%	55%	6.637 €	**-0,9%**	6.754 €	**0,9%**
OPEX_Network_Op	-55%	55%	6.654 €	**-0,6%**	6.736 €	**0,6%**
MonthFeeHH	-60%	60%	6.674 €	**-0,3%**	6.716 €	**0,3%**
OPEX_Equipment	-50%	50%	6.687 €	**-0,1%**	6.703 €	**0,1%**
MonthFeeSME	-60%	60%	6.690 €	**-0,1%**	6.701 €	**0,1%**
ActivationFeeHH	-60%	60%	6.691 €	**-0,1%**	6.700 €	**0,1%**
OPEX_Cable	-55%	55%	6.691 €	**-0,1%**	6.699 €	**0,1%**
OPEX_Installation(Equip)	-55%	55%	6.692 €	**-0,1%**	6.699 €	**0,1%**
CAPEX_Housing	-50%	50%	6.693 €	**0,0%**	6.698 €	**0,0%**
RequiredDsBandwithHH	-60%	60%	6.695 €	**0,0%**	6.697 €	**0,0%**
ActivationFeeSME	-60%	60%	6.695 €	**0,0%**	6.696 €	**0,0%**
OPEX_Housing	-50%	50%	6.695 €	**0,0%**	6.695 €	**0,0%**
PotentialNomadic	-60%	60%	6.695 €	**0,0%**	6.695 €	**0,0%**
RequiredDsBandwithSME	-60%	60%	6.695 €	**0,0%**	6.695 €	**0,0%**
RequiredDsBandwithNomadic	-60%	60%	6.695 €	**0,0%**	6.695 €	**0,0%**
ActivationFeeNomadic	-60%	60%	6.695 €	**0,0%**	6.695 €	**0,0%**
MonthFeeNomadic	-60%	60%	6.695 €	**0,0%**	6.695 €	**0,0%**
OPEX_Lease	-55%	55%	6.695 €	**0,0%**	6.695 €	**0,0%**

Table 15 shows that if the technology penetration rate decreases 60%, the cost per subscriber increases 278%. However, if the penetration rate increases 60%, the cost per subscriber decreases 39,7%. The CAPEX (for civil works) is the second biggest variable with impact in the cost per subscriber.
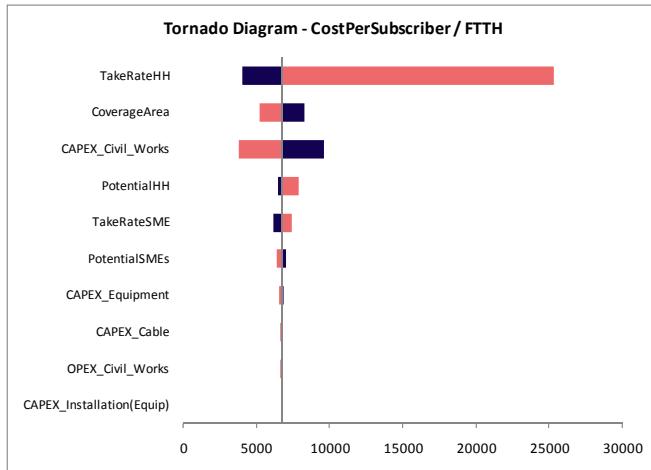

Figure 5.   Sensitivity Analysis for FTTH: Cost per Subscriber

Figure 5 shows the effect of these input variables on the output variables. These diagrams create base, low and high value scenarios for each input variable. The output variables used in our analysis are: Cost per subscriber, Cost per Homes Passed, End cash balance, Payback period NPV, IRR, CAPEX, and OPEX.

This tornado diagram shows the effect of the input variables on the output variables. The red bars represent the Output for Low Value (Negative Variation in Parameter) and the blue bars represent the Output for High Value (Negative Variation in Parameter).

IV.   Conclusions

This work presents a techno-economic model framework to support the bandwidth and mobility trends of access networks. The proposed approach separates the area into static and nomadic (mobility) users. In the static layer, users are stationary and normally require data, voice, and video quality services. These subscribers demand great bandwidth. In the nomadic layer (or mobility layer) the main concern is mobility, and normally, the required bandwidth is smaller than in static layer.

The produced results can analyze how the costs vary from region to region, calculating the cost per user, cost per homes passed, payback period, NPV, IRR, end cash balance, CAPEX, OPEX, and so on. The proposal tool performs a detailed comparison of the different broadband access technologies in several scenarios. For each access network, the model chooses the best solution, based in the output results.

The sensitivity analysis shows the effect of the input variables on the output variables and identifies the critical parameters for several technologies. With this information it is possible to define better strategies for building broadband access networks.

References

[1]   C. Sarrocco and D. Ypsilanti, "Convergence and Next Generation Networks," OECD,CISP(2007)/Final, June2008.

[2]   V. Vittore, "Broadband in High-Growth Economies," in *Breaking the Barriers - Transformation to the Digital Life*. J.-P. Lartigue, Ed. Alcatel-Lucent's, 2008, pp. 317-324.

[3]   J. Wellen, "High-Speed FTTH Technologies in an Open Access Platform - the European MUSE Project," in *Broadband Optical Access Networks and Fiber-to-the-Home: Systems Technologies and Deployment Strategies*. C. Lin, Ed. John Wiley & Sons, 2006, pp. 139-166.

[4]   X. Fernando, "Broadband Access Networks," IEEE International Conference on Signal Processing, Communications and Networking, 2008, pp. 380-383.

[5]   M. Peng and W. Wang, "A Unified Architecture and Key Techniques for Interworking between WiMAX and Beyond 3G/4G Systems," *Wireless Personal Communications*, vol. 43, no. 1, pp. 1-24, Oct.2007.

[6]   WiMAX Forum, "Driving the adoption of interoperable wireless broadband worldwide," WiMAX Forum,Sept.2008.

[7]   J. P. Pereira, "A Cost Model for Broadband Access Networks: FTTx versus WiMAX," Second International Conference on Access Networks, 2007, pp. 1-8.

[8]   J. P. Pereira, "Broadband Access Technologies Evaluation Tool (BATET)," *Technological and Economic Development of Economy*, vol. XIII, no. 4, pp. 288-294, 2007.

[9]   J. Baker, T. Cagenius, C. Goodwin, M. Hansson, and M. Hatas, "Deep-fiber broadband access networks," *ERICSSON REVIEW*, vol. 84, no. 1, pp. 4-8, 2007.