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ANÁLISE TECNICO-ECONÓMICA DE REDES DE ACESSO: FERRAMENTAS DE DECISÃO

TECHNO-ECONOMIC ANALYSIS OF ACCESS NETWORK: DECISION TOOLS

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Análise Técnico-Económica de Redes de Acesso: Ferramentas de Decisão

Techno-Economic Analysis of Access Networks: Decision Tools

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor A. Manuel Oliveira Duarte, Professor Catedrático do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e da Professora Doutora Raquel Matias da Fonseca, Professora Auxiliar do Departamento de Engenharia e Gestão Industrial da Universidade de Aveiro

29 de Julho de 2013

Dedico este trabalho aos meus pais, Pureza e Aníbal,

…

o júri

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agradecimentos

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A todos Vós,

Muito Obrigado

palavras-chave

Novas Redes de Acesso em Redes de Telecomunicações; HFC protocolos, estrutura, dimensionamento análise técnico-económica.

resumo

O recente crescimento de consumo de internet e televisão por cabo desencadeou a necessidade de novas redes de acesso. O mundo das telecomunicações tornou-se num negócio competitivo entre as operadoras.

As estratégias de competitividade são agora com baseadas em qualidade do serviço e na acessibilidade dos preços a todas as categorias da população. Para garantir estes requisitos é necessário inovar em equipamentos e meios de distribuição. A implantação de novas redes de acesso tornou-se crucial na sociedade, mas a recente crise económica mundial forçou um dimensionamento cuidado para garantir o máximo lucro possível no negócio.

Portanto esta dissertação apresenta uma análise económica e financeira da implementação de uma rede HFC. Mostra a estrutura da rede e as suas características tecnológicas, além disso explica como lidar com problemas no dimensionamento da rede: a incerteza espacial associada ao processo de adesão dos utilizadores e como lidar com consumo em excesso de largura de banda, também causado pelos utilizadores. Por fim realiza o estudo da instalação da rede HFC em três tipos diferentes de cenários e expondo os resultados económicos obtidos, permitindo a conclusão sobre a viabilidade destes projetos.

keywords

Next Generation Access Networks; HFC protocols, structure, dimensioning, techno-economic analysis.

abstract

The recent growth in Data Traffic and Cable Tv consumption triggered the need for new access networks and the world of Telecommunications has become a very competitive business among service providers.

The strategies of competitiveness are now based on quality of services and affordable prices to all classes of the population. To guarantee these requirements, an equipment and distribution facilities innovation was necessary. The deployment of Next Generation Access Networks (NGA) has become crucial in society, but the recent world economic crisis has forced a careful dimensioning to produce the most profit possible with small investments.

This dissertation presents a techno-economic analysis of a HFC network implementation. The network structure and technologic characteristics are presented, along with explanation of how to deal with problems in the network dimensioning: as spatial uncertainty associated with the adhesion process of the users and the surplus consumption of bandwidth by them. Finally, the study of the network implementation in three different sorts of areas is shown and the economic results obtained are exposed, providing the viability of these projects.

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List of Acronyms

3D	*-3 Dimensions*
ADSL	*-Asymmetric Digital Subscriber Line*
AM	*-Amplitude Modulation*
ATM	*-Asynchronous Transfer Mode*
BPI	-Baseline Privacy
BW	*-Bandwidth*
CAPEX	*-Capital Costs*
CATV	*-Cable Television*
CM	*-Cable Modem*
CMTS	*-Cable Modem Termination System*
CO	*-Central Office*
CSMA/CD	*-Carrier Sense Multiple Access with Collision Detection*
DECT	*-Digital Enhanced Cordless Telecommunications*
DOCSIS	*-Data Over Cable Service Interface Specification*
DS	*-Downstream*
DSL	*-Digital Subscriber Line*
DSLAM	*-Digital Subscriber Line Access Multiplexer*
DTT	*-Digital Terrestrial Television*
EC	*-European Commission*
EDGE	*-Enhanced Data rates for GSM Evolution*
FDM	*-Frequency Division Multiplexing*
FM	*-Frequency Modulation*
FM	*-Frequency Modulation*
FTTB	*-Fiber to the Building*
FTTC	*-Fiber to the Curb*
FTTCab	*-Fiber to the Cabinet*
FTTH	*-Fiber to the Building*
FTTH	*-Fiber to the Home*
FTTN	*-Fiber to the Node*
FTTP	*-Fiber to the Premises*
GPRS	*-General Packet Radio Service*
GSBL	*-Grupo de Sistemas de Banda Larga (Broadband Systems Group)*
GSM	*-Global System Mobile*
HCS	*-Header Checksum*
HD	*-High Definition*
HDR	*-Header*
HDSL,	*-High-Bit-Rate Digital Subscriber Line*
HE	*-Head-End*

HE	*-Head-End*
HFC	*-Hybrid Fiber-Coax*
HHP	*-House Holds Passed*
HSPA	*-High Speed Packet Access*
ICT	*-Information and Communications Technology*
IP	*-Internet Protocol*
IPTV	*-Internet Protocol Television*
IR	*-Interest Rate*
IRR	*-Internal Rate of Return*
ISDN	*-Integrated Services Digital Network*
ITU	*-International Telecommunication Union*
ITU-T	*-International Telecommunication Union – Telecommunication*
LTE	*-Long Term Evolution*
MAC	*-Media Access Control*
MAC	*-Media Access Control*
MP	*-Market Penetration*
MPEG	*-Moving Picture Experts Group*
MPEG	*-Moving Picture Experts Group*
MSO	*-Multiple Service Operator*
NGA	*-Next Generation Access*
NPV	*-Net Present Value*
ON	*-Optical Node*
OPEX	*-Operational Costs*
OSI	*-Open Systems Interconnection*
OSI	*-Open Systems Interconnection*
PDA	*-Personal Digital Assistant*
PON	*-Passive Optical Network*
Pop	*-Population*
POTS	*-Plain Old Telephone Service*
PSTN	*-Public Switched Telecommunications Network*
QAM	*-Quadrature Amplitude Modulation*
QoS	*-Quality of Service*
QPSK	*-Quadrature Phase Shift Keying*
RADSL	*-Rate-adaptive Digital Subscriber Line*
RF Amp	*-Radio Frequency Amplifiers*
RF	*-Radio Frequency*
RFoG	*-Radio Frequency over Glass*
S-CDMA	*-Synchronous Code Division Multiple Access*
SCM	*-Sub Carrier Multiplexing*
SD	*-Session Density*

SDSL	-*Symmetric Digital Subscriber Line*
SMS	-*Short Message Service*
SPA	-*Serial Port Adapter*
SPI	-*Serial Peripheral Interface*
STB	-*Set-Top Box*
TCP	-*Transmission Control Protocol*
TDM	-*Time Division Multiplexing*
TDMA	-*Time Division Multiple Access*
TV	-*Television*
UDP	-*User Datagram Protocol*
UHF	-*Ultra High Frequency*
UMTS	-*Universal Mobile Telecommunications System*
US	-*Upstream*
U-TRAN	-*Universal Terrestrial Radio Access Network*
VDSL	-*Very-high-bit-rate Digital Subscriber Line*
VHF	-*Very High Frequency*
VOD	-*Video on Demand*
VoIP	-*Voice over Internet Protocol*
VSB	-*Vestigial Side Band*
WAN	-*Wide Area Network*
WDM	-*Wavelength Division Multiplexing*
WLAN	-*Wireless Local Area Network*
xDSL	-*Digital Subscriber Line*

1. Introduction

1.1 Objectives

The main objective of this dissertation is to contribute for a better understanding of the relations between telecommunications access networks technologies and its underlying economics, in the specific context of HFC (hybrid fiber coax) technologies.

HFC is an access network technologies that has matured over the last 2 decades in portuguese territory. It combines both optical fiber and coax physical media.

In spite of its maturity several changes still remain in the engineering of HFC networks, namely in its dimensioning. To understand the dimensioning of a network and to achieve the above objective, several decision support tools were developed or adapted.

With the increasing competition coming FTTx technologies promoted by incumbent telecom operators it's vital to leverage the full capability of HFC networks promoted by cable TV operators. This is true in both areas where HFC is already deployed and in greenfield areas. The main leverage factor of HFC is its extended throughput (in excess of 100Mbits per second).

1.2 Outline of the dissertation

The first chapter contains a brief introduction, setting the motivation, background and framework of the dissertation. The following explains the access networks solutions technologies present in the current world of telecom.

The next section Present the state of the art of HFC technologies. The subsequent chapter characterizes the dimensioning of the access network highlighting points like the equipment capacity and granularity, geographic and demographic analysis associated with the spatial uncertainty in the process of adhesion of users and the consumption of bandwidth for users.

In chapter 5 the Economic and Financial Analysis is presented, which includes potential market study, taking into coverage areas, market penetration, capital and operating costs and expected revenues and the analysis of results obtained in the implementation of HFC. Finally, the conclusions and future works of this study are listed in chapter 6.

1.3 Motivation

When I was kid, I remember my mother trying to have internet access at home and the operator said that my house was too far from the central office so there was no coverage for transmission speeds necessary to Internet. At that precise moment, a desire grew on me to understand what was happening? Why were my friends from school able to play online games, while I couldn't?

Looking back in time to the last 25 years, it is impressive to realize how telecommunications evolved over this period. From times when only a reduced number of public television channels existed, mobile phones looked more like big pieces of luggage and internet tariffs were only at the reach of people with big salaries. We reached a moment when TVs have more than one hundred channels available, mobile phones can be lost in ours pockets and internet is included on public needs with financial support provided.

The telecommunications service is a business. A business is any economic activity with the purpose of generating profit and therefore the planning and design of the implementation of a new network access must be carefully studied in order to make it the most profitable possible.

The vast majority of developed countries, such as Portugal already have internet and cable TV coverage for almost the entire country. But many official portuguese speaking countries and others like them are still in the process of developing the implementation of new telecommunication networks with internet access and cable TV, turning them into a possible target to great business.

1.4 Background

Since the end of the nineteenth century, where the first phone call was made, until the present day, the telecommunications world was never the same, suffering drastic changes and improvements. With an impressive speed, new thrusts of science would give the world other types of machinery that, with respect to time and ingenuity, even renowned futurists wouldn't dare to predict: rapidly succession came with the transistor in 1947 and the laser in 1953, which came to modify diversified manufacturing methods and introduced new devices for communications [1]. After the miniaturization in electronics, began the era of communications satellites in 1962, which enjoyed superb efficiency in the field of telephony, telegraphy, television, meteorology and others [1].

During the 1980s and 1990s, technologies like ISDN (Integrated Services Digital Network) and ATM (Asynchronous Transfer Mode) have competed with IP as the dominant networking technology for multimedia applications, including convergent voice, video and data services. By this time there was still doubt about the capabilities of IP to handle packet transmission priority for real-time application and supporting billing and security issues [2]. An interesting fact is that VocalTec company built the first commercial application of voice over IP, demonstrating the potential of IP technology for voice transmission and real-time applications.

The voice over IP technology evolved and less than 10 years later, the incumbent telecommunications services providers started to show interest in deploying this technology to replace their PSTN (Public Switched Telecommunications Network) networks [2]. By now we see almost all of telecommunication operators replacing the circuit-switched technology by a new one based on pack-switched technology (IP) because the last one have shown a lot of potential and offers a unique opportunity to provide integrated solutions to the costumers. This type of concept will be necessary a framework which integrates the technological, economic and political issues able to start a revolutionary change in our daily life [3].

In business terms on the European area, initially until the 80's principles of the telecommunications monopoly were managed by public entities and the states of each country, with partnerships with private companies in the business [4]. This method was due to the need to provide coverage to the entire population of television and telephone network, offering a fast technological growth in the countries.

With the liberalization and privatization of the telecom operators, the market is rapidly evolving, with competition between these operators that offer better products and correspondingly attracting more users. As such, regulators are designed to control and fight the unfair competition. Telecommunications have evolved, the number of services has grown, membership has increased and the proportion of multimedia traffic and the bandwidths followed [5]. The need for new equipment, infrastructure and network architectures ted to the NGA. It is expected that the investment in NGA may have a quite significant social and economic impact in sectors like education, health, social work, mobility, logistics, security and justice, and contribute to a new generation of qualified jobs.

1.5 Framework

According to the EC Recommendation C (2010) 6223 [6] - "next generation access networks (NGA) are wired access networks, which consist wholly or partly of fiber optic elements, and which are capable of providing access broadband with more advanced features (such as increased transmission capacity) compared to that provided by the network existing copper. In most cases, the NGA result of improvements in access network of copper or coaxial existing ".

An access network connects subscribers with the world global network, through a service provider (connects the end-users) [7]. The access network is the less shared part of the network and its main function is to provide access to the same information data, voice and video through service. Low-cost technologies are mandatory in the access network. Services like HD or 3D TV, Video on Demand, Interactive Gaming, IPTV, VoIP are demanding more bandwidth when comparing with the POTS. The increase of demand for information and new services through different networks induced a need to improve and innovative the technologies in use. This search to upgrade the quality of life obligates the restructuration of infrastructures, taking into account the population and geographic features of each city.

Comparing the different areas of a telecommunications network (Core, Metro and Access) the technological development lays in that order: due to the granularity of the components that make up these classes. The Core Network can cover a large area of users needing a technological advancement to not allow flaws and provide excellent service. On the other hand, it’s the Network Access that contains components that cover a larger area and also reveal more cost effectiveness requirement, because with a much lower granularity factor, more elements near the consumers are needed and this big number of components generates more costs.

So the study of an implementation of a new access network needs to be developed in a way studied to verify the costs and the optimal return cost. The next figure 1 compares the different areas of a telecommunications network (Core, Metro and Access) in the matters of requirements:

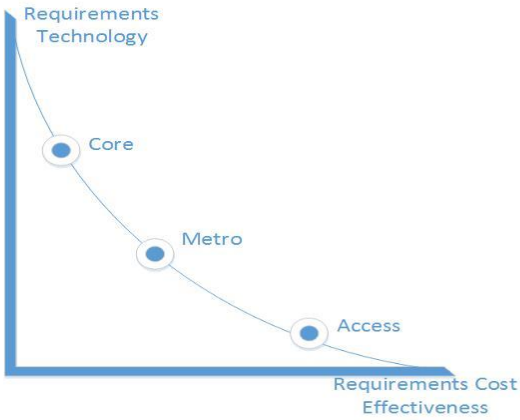


Figure 1 – Telecommunications Networks - Requirements Technology “vs” Requirements Cost Effectiveness (Draw by the author)

The Internet information and Communication Technology (ICT) usage become significantly omnipresent in today’s society. As indicated in [8], ICT shows what in the end of 2011 2.3 billion people were online and the percentage of internet user continues to grow worldwide.

In developed countries the percentage is higher than 70%, and in developing countries, the number of Internet users doubled between 2007 and 2011, Places like Brazil, China and India with good services Internet provider and with huge number of habitants can make the number of online subscribers double (in the end of 2011 just a quarter of China population were online [8]). Figure 2 shows the level of Internet penetration worldwide:

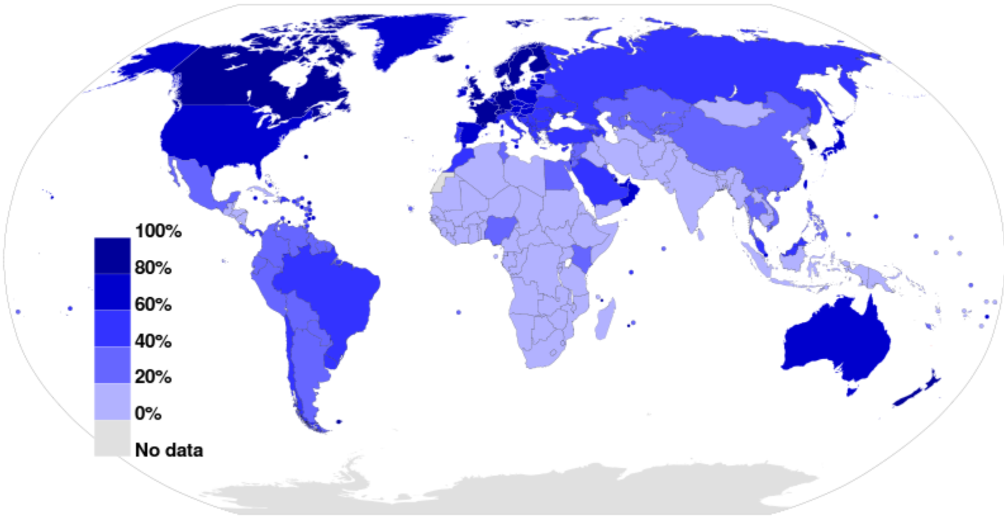


Figure 2 – A world map colored to show the level of Internet penetration (number of Internet users as a percentage of a country's population), (April 2012) [9]

It is important to remember that younger people use more broadband than older people [9], turning this world percentage of subscription influenced, by that and the preexistence of NGA. The consumers of internet by age and country state development are represented on the following figure 3:

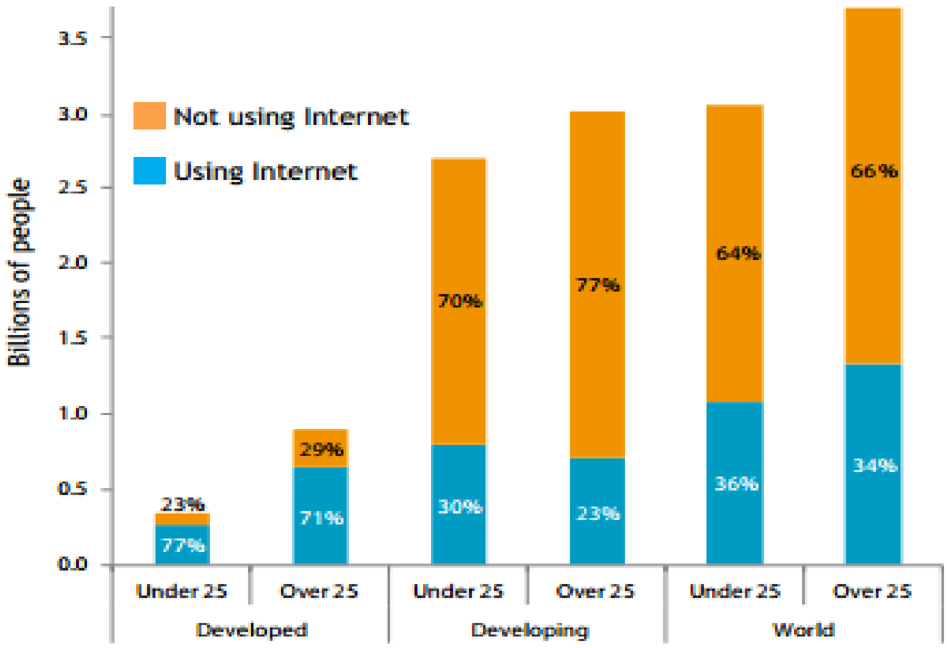


Figure 3 – Internet Users by age and by country state development level, 2011 [10]

The networks feed the Metro and Core networks by gathering data from the end users. The two main contenders are CATV and phone companies. Since existing physical infrastructures are available, operators try to combine their networks to provide data services such as high speed Internet access. According to the paper [10], from 1.8 billion households worldwide, one third have Internet or/and Cable TV access.

It is clear that broadband access penetration is increasing rapidly, and higher bandwidth access technologies are required, so to continue the performance and guarantee quality of services provided the network architecture and equipment has to be in constant evolution. The analysis of NGA is important to prevent and haste the necessary resources to its implementation, on each specific coverage area, because nowadays what gives rhythm to investment is the financial return expected.

2. Access Network: Overview

The access networks establish the link between the customers and the switches on the local exchanges. These wireless networks may or may not use cables using different numbers of cables, frequency spectra and technologies. The majority of the infrastructures of access networks consist of copper wires and coaxial cables, using analog transmission techniques. These materials are the main factors responsible for transmission speeds very limited.

Initially the network traffic access was mostly voice, having evolved to a balanced one between voice and data. This change in the type of traffic requires the coexistence of a switching infrastructure between voice and data separate. With the addition of the television service to this paradigm, bandwidth and transmission speeds per customer needed to be increased, leading to the formation of hybrid networks (fiber / coaxial) which allowed a fast and inexpensive implementation for telecom operators.

Currently optic fiber (FTTx) is the most suitable resource for NGA, allowing the implementation of existing applications and providing greater bandwidth, opening new horizons in terms of services, through a superior service quality and a reduction of degradation in terms of latency or contention rate.

2.1 Technology Solutions

This section presents a short briefing of the different transmission technologies present in the access networks currently implemented. These technologies and transmission media can be used in the various subsegments which can be split in different sections (wired and wireless networks), as can be seen in the figure 4:

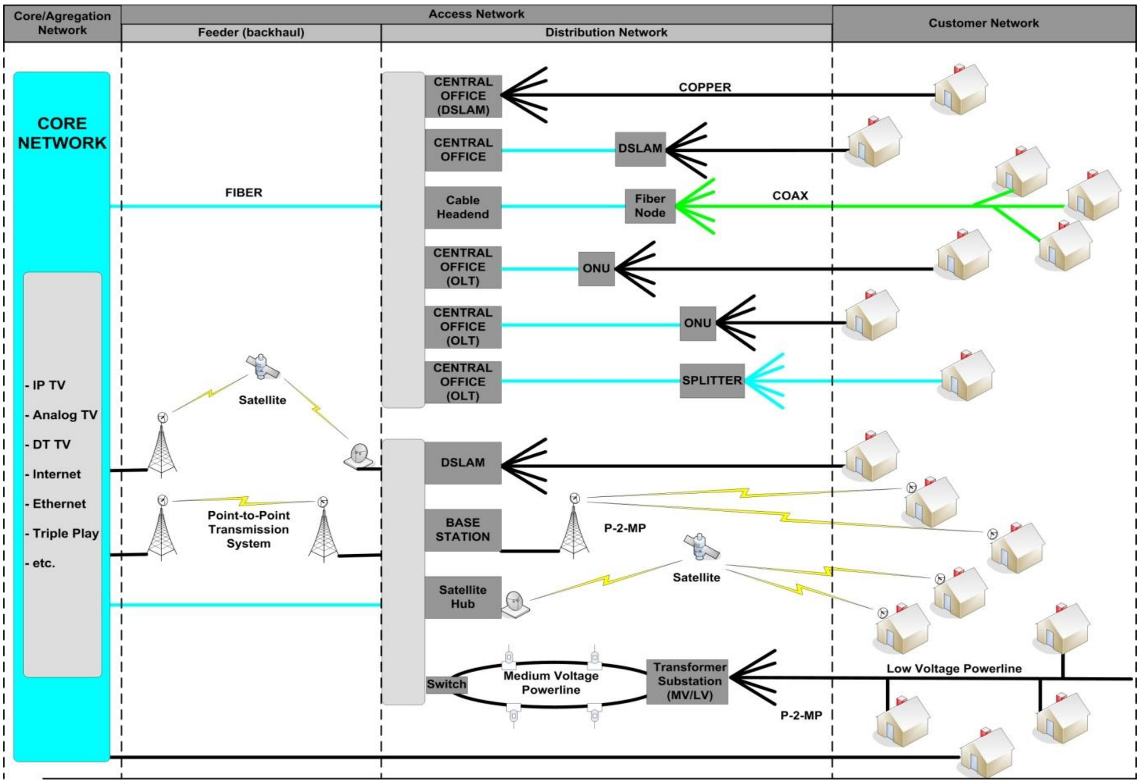


Figure 4 - Different technological scenarios for Access Networks [11]

2.1.1 Wired Networks

A wired network requires network cables or cords to make connections between computers and other network devices. On this section is explained some of this networks.

2.1.1.1 Fixed Telephone Network

The fixed telephone network was created to allow voice communication POTS and consists a network of twisted pairs of copper, the PSTN. The growing demand for this service, led to the necessity of elements that permit connections on a more efficient way than the manual switching commonly used. Automatic switches were then introduced, allowing the automatic selection of the destination of the call. New digital technologies appeared then the ISDN that would allow greater network integration, becoming possible to transmit voice and data traffic on the same network [12].

2.1.1.2 xDSL Network

The xDSL networks emerged in an attempt to take maximum advantage of the existing infrastructure network PSTN, through the development of modulation techniques and spectral compression, making them capable of transmitting up to speeds above the previous ones. This technology establishes a permanent circuit between the user and the service provider, offering a higher transmission speed. DSL-based networks are thus advantageous because they can provide the bandwidth to allow the use of several services and applications such as VoIP and IPTV. However, it presents also some disadvantages, since the performance is highly affected by distance. There are different speed DSL technologies that provide symmetrical or asymmetrical, such as ADSL, SDSL, VDSL, HDSL, IDSL and the RADSL [13].

2.1.1.3 HFC (Hybrid Fiber Coax) Network

The HFC networks present a tree structure, using coaxial cable distribution zones and fiber optics in longer sections of the network. This type of access network is in focus in this dissertation, being explained in detail ahead on chapter 3.

2.1.1.4 FTTx Networks

FTTx (Fiber to the x) is a generic term to designate any type of telecommunications network which uses optical fiber to replace all or part of the copper access loop from previous networks. Depending on the point of termination of the optical fiber, these architectures have several designations: FTTN (Fiber To The Node), FTTCab (Fiber To The Cabinet), FTTC (Fiber To The Curb), FTTP (Fiber To The Premises), FTTB (Fiber to The Building) and FTTH (Fiber To The Home).

The speeds of fiber-optic and copper cables are both limited by length, but copper is much more sharply limited in this matter. The demand for more content, greater speed and new communication protocols is exploding across many global markets. Services such as High Speed Internet Access, Voice over Internet, Video-on-Demand, and High Resolution TV Broadcasting represent substantial new revenue opportunities for Telecommunications Operators and Network suppliers [14].

2.1.2 Wireless Networks

A wireless network consists of multiple stations communicating with radio broadcast. This chapter expounds the most relevant wireless networks technologies solutions.

2.1.2.1 Free Space Broadcasting

Wireless networks are characterized by the ability to direct the several users at the same time and use the electromagnetic spectrum as a transmission medium. An example of these networks is the ancient television broadcast system in free space, which used radio frequency signals (radio signals transmitted are modulated onto frequency carriers Frequency Modulation (FM)) in the VHF (Very High Frequency) and UHF (Ultra High Frequency) bands. The signals from the transmitter were sent to the user through local transmitters that receive the signal and amplify it [12]. This system was replaced by scanning transmission (DTT - Digital Terrestrial Television). This new system uses radio frequency signals, in the same way as traditional television, allowing however the receptions of multiple channels in a single frequency range.

2.1.2.2 Cellular Networks

The **GSM** (Global Systems for Mobile communications) is the most widely used mobile telephone network in Europe. It is a telecommunications system that has the capacity to transmit data, voice, and some additional services very common in mobile communications systems (SMS, call forwarding, etc.).

The **UMTS** (Universal Mobile Telecommunications System) is a technology for third generation mobile communications. It was designed in order to keep the overall success of mobile communication system GSM (second generation), a continuation of GPRS, allowing provide multimedia services at higher speeds. The **HSPA** (High Speed Packet Access) is a technology that allows higher data rates than UMTS-based networks.

The **LTE** (Long Term Evolution) has arisen due to the recent increased use of data exchange and emergence of more and more applications, such as online gaming, mobile TV, and Web 2.0. It is expected that the LTE radio access which is called Evolved UMTS Terrestrial Radio Network (E-UTRAN) substantially increases the flow rate of each end user.

2.1.3 Wireless LAN Network

The WLAN (Wireless Local Area Network) supports network communication over short distances (ex. home, firm) using radio or infrared signals. The following topics show some technological scenarios for WLAN Networks.

2.1.3.1 Wi-Fi

The Wi-Fi technology was developed to provide short range wireless, giving users greater convenience in their daily lives. This technology is generally used for maximum distances of 30 meters and 90 meters indoors and outdoors [11].

2.1.3.2 WiMax

WiMax is a wireless technology that is intended to be an alternative to DSL and cable. This technology is far superior to Wi-Fi since it operates at licensed frequencies, which allows the use of higher transmission powers [11]. However, and similarly to Wi-Fi, the available bandwidth is also shared by all users who are connected to the network simultaneously, the consequently as the number of users increase, smaller will be the bandwidth available for each one.

2.1.3.3 Bluetooth

Bluetooth is a low-range wireless network technology used for linking devices to one another without a hard-wired connection. It does not required a direct line of sight to communicate and he aim is to transmit voice or data between devices with low-cost radio circuits, over a range of about ten to just under a hundred meters, using very little power [11]. Designed mainly for linking devices on short distances became more and more commonly used in mobile phones, allowing them to communicate with computers or PDAs.

2.1.3.4 Zigbee

The Zigbee technology is specified for a set of high level communication protocols using small, low-power digital radios, such as wireless headphones connecting with cell phones via short-range radio, presenting a simpler and less expensive solution than other WPANs [13].

2.1.3.5 DECT

The DECT (Digital Enhanced Cordless Telecommunications) is used for digital phones. Standard fully specifies means for a portable unit such as a cordless telephone to access a fixed telecoms network via radio [14].

3. HFC (Hybrid Fiber Coax) Networks: State of the Art

As stated previously, the main focus of this dissertation is present HFC networks characterization and several engineering challenges of dimensioning.

HFC networks are the result of the evolution of the old CATV standards through introduction of optical fiber transmission in its feeder and distribution segments and bidirectionality all the way. Figure 5 [16] illustrates the basic structure of the old CATV networks and a small overview of present day HFC networks.

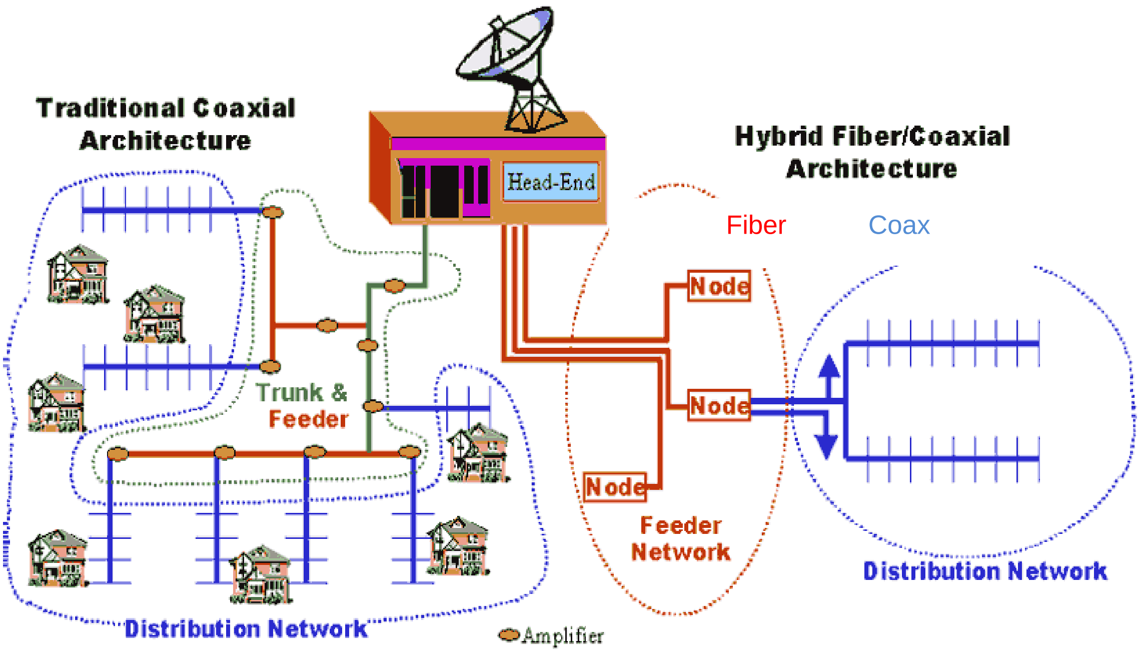


Figure 5 – Traditional CATV structure vs HFC structure [16]

One of the crucial technological factors behind the introduction of HFC technologies was the adoption of DOCSIS (Data Over Cable Service Interface Specification) protocols. These protocols manage the joint transmission of video, data and voice over a shared media as in this case of the coaxial cables.

3.1 CATV

The CATV networks (Cable Television) were created for transmission of television over long distances. Cable television involves the distribution of a number of television channels collected at a central location (Head-End) to subscribers within a community through a network of coaxial cables.

Cable networks were initially only broadcast (meaning that a single-operator would send the same signal to all costumers), but with the evolution of telecommunications and do maintain the great adhesion of subscribers. CATV networks were forced to make possible two-way independent communication subscriber, in order to operate simultaneously with the data service and VoIP [17].

The CATV network uses the signal of a laser with SCM (Sub Carrier Multiplexing) over a bandwidth between 50 and 550 MHz. In this band the coaxial cable can carry about 70 TV signals in AM-VSB. A spectral window between 5 and 40 MHz is also available, for return signals [17]. The next image shows CATV frequency spectrum:

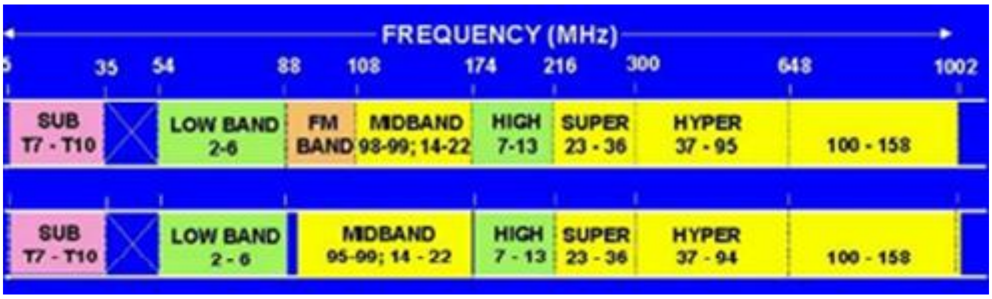


Figure 6 – Frequency Spectrum Organization for the different types of telecommunications (Annsgarden Telecom) [18]

The need to implement interactive services originated an upgrade of CATV to allow communication in both directions.

3.2 DOCSIS

Currently the most common HFC networks are based on DOCSIS technology. The basic attributes of this technology are the following:

- Combines the transmission of video (in analog or digital format, eg MPEG-2) and data [19];
- Specifies modulation techniques and spectrum partition;
- Defines the interface requirements for modems involved in high-speed data distribution over cable television system networks both on the user side (CM - Cable Modems) and on the operator side (CMTS - Cable Modem Termination System);
- It is based on a Point-to-Multipoint architecture, targeted to the transmission in shared media (coaxial cable) [20]. TDM (Time Division Multiplexing) downstream and TDMA (Time Division Multiple Access) upstream techniques are used as described ahead in this section.

The following pictures 7 and 8 illustrate the basic functioning of point-to-multipoint structure and HFC – DOCSIS structure, respectively:

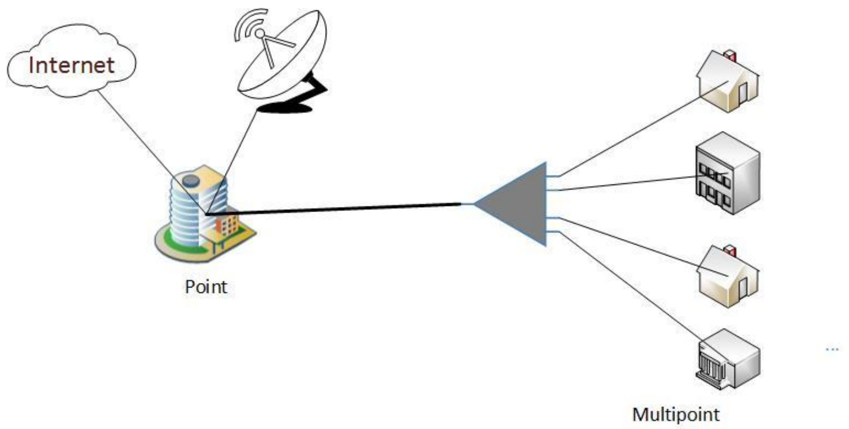


Figure 7 – Point-to-Multipoint model (Draw by the author)

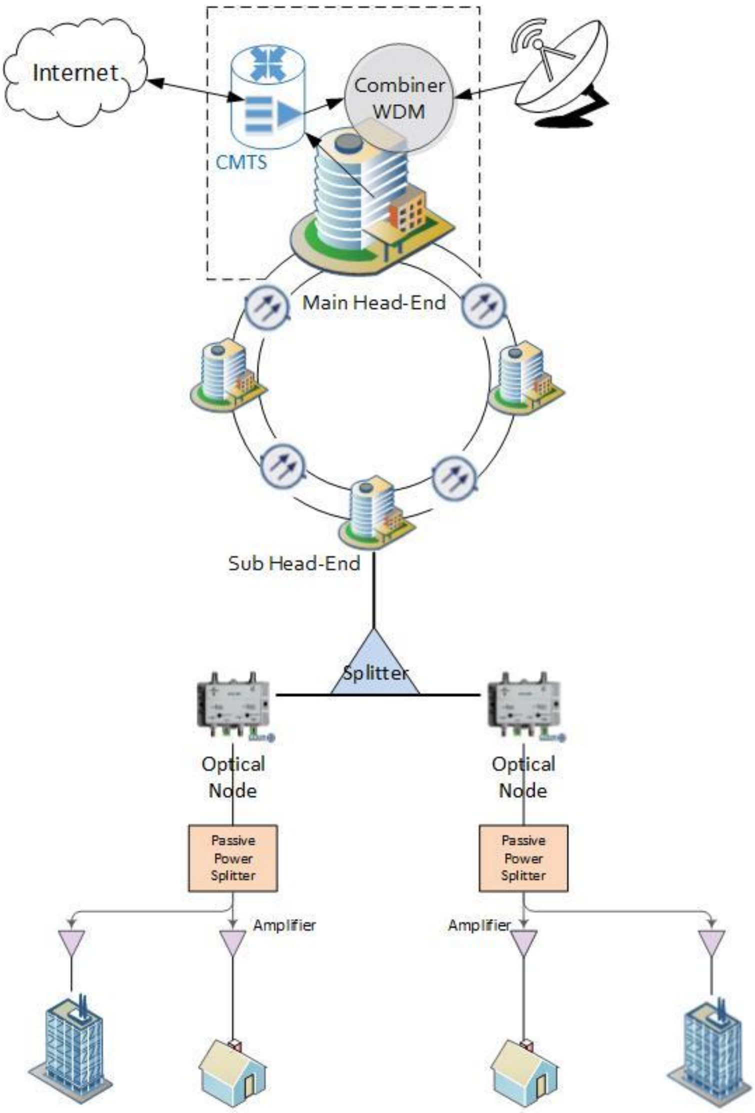


Figure 8 – DOCSIS Structure (Draw by the author)

DOCSIS was developed by CableLabs in partnership with other companies that include ARRIS, BigBandNetworks, Broadcom, Cisco, Conexant, Correlant, Harmonic, Intel, Motorola, Netgear, Terayon, and Texas Instruments [20].

There are two key components in the DOCSIS architecture [21]:

– Cable Modem (CM) located at the customer premise;

– Cable Modem Termination System (CMTS), located at the head end of service providers and is used to aggregate traffic from multiple Cable Modems and then communicate with the backbone network.

DOCSIS specifies modulation schemes and the protocol for exchanging bidirectional signals between these two components over cable. The standardization branch of the ITU (International Telecommunication Union) (ITU-T) has approved several versions of DOCSIS as international standards: DOCSIS 1.0 in ITU-T Recommendation J.112 Annex B (1998), DOCSIS 2.0 in ITU-T Recommendation J.122 (2007) and DOCSIS 3.0 in ITU-T Recommendation J.222 [21].

• ITU-T approved various versions of DOCSIS, presents in next table 1:

Direction	**Downstream**		**Upstream**
Version	*DOCSIS*	*EuroDOCSIS*	*Both*
1.x	38 Mbit/s	50 Mbit/s	9 Mbit/s
2.0	38 Mbit/s	50 Mbit/s	27 Mbit/s
3.0 4channel	152 Mbit/s	200 Mbit/s	108 Mbit/s
3.0 8channel	304 Mbit/s	400 Mbit/s	108 Mbit/s

Table 1 – DOCSIS ITU-T protocol versions [22]

The following table 2 shows the specifications of the OSI Layers of DOCSIS:

OSI	**DOCSIS**	
Higher Layers	Applications	DOCSIS Control Messages
Transport	TCP/UDP	
Network	IP	
Data Link	IEEE 802.2	
Physical	***Upstream***	***Downstream***
	TDMA (mini-slots) 5 - 42(65) MHz QPSK/16-QAM	TDM (MPEG) 42(65) - 850 MHz 64/256-QAM ITU-T J.83

Table 2 – OSI Layers of the Modems DOCSIS (The values in brackets refer to the EuroDOCSIS) [22]

3.2.1 Modulation

DOCSIS provides functions available at OSI layers 1 (physical) and2 (MAC).

- Physical layer (modulation) – 64-level or 256-level QAM (64-QAM or 256-QAM) is used for modulation of downstream data – QPSK or 16-level QAM (16-QAM) is used for upstream modulation [22].

DOCSIS 2.0 specifies 32-QAM, 64-QAM and 128-QAM also be available for upstream use.

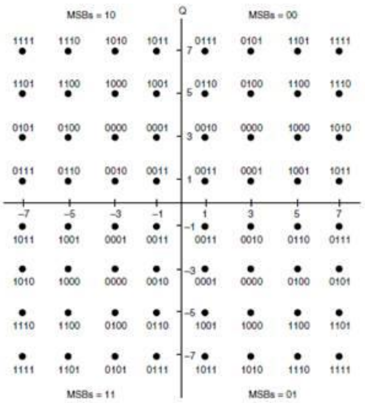
- MAC layer – DOCSIS employs a mixture of deterministic access methods, specifically TDMA for DOCSIS 1.0/1.1 and both TDMA and S-CDMA for DOCSIS – S-CDMA scatters digital data up and down a wide frequency band and allows multiple subscribers connected to the network to transmit and receive concurrently – In contrast to the pure contention-based MAC CSMA/CD employed in older Ethernet systems (there is no contention in switched Ethernet).

For DOCSIS 1.1 and above the MAC layer also includes extensive Quality of Service (QoS) features that help the efficient support of applications, like Voice over IP, that have specific traffic requirements, such as low latency [23].

The data in the downstream direction is modulated using the 64-QAM or 256-QAM [23]. On 64-QAM for each symbol sent are used 6 bits, from which one bit is used for error correction, leaving 5 bits for data. The standard determines 1Hz/baud (symbols per second) of modulation rate, meaning that the downstream data can be received at 30 Mbps (5 bits/Hz x 6 MHz) [24].

On 256-QAM modulation type the symbol rate is 5 MS per second, meaning the downstream data can be received at 42.9 Mbps. For a more detailed analysis of bandwidth per channel and package see Appendix A.

The figure 9 and 10 shows an example of the 64-QAM and QPSK constellation, respectively:



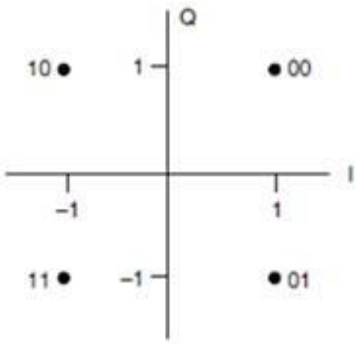


Figure 9 – Constellation of 64-QAM [24]   Figure 10 – Constellation of QPSK [25]

The upstream data band uses frequencies very susceptible to noise and interference, so the QAM modulation is not used in favor of QPSK. These data occupies the lower band which is divided into 6 MHz channels.

In QPSK modulation are used 2 bits per symbol. As mentioned above, the standard specifies 1Hz/baud therefore the data will be sent in upstream 12Mbps (2 bits/Hz x 6 MHz).

Figure 11 illustrates how communication between CMTS and CM works:

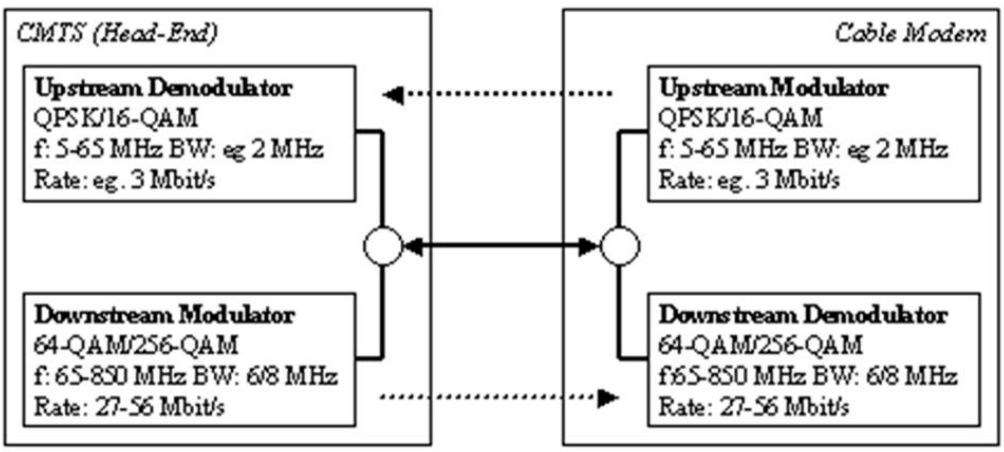


Figure 11 – CMTS and CM communication modulation [21]

3.2.2 Bandwidth

The information transmitted from the head-end to the consumer (downstream) use a band from 50 to 750 MHz while the information transmitted from the consumer to the network (upstream) generally uses a bandwidth of 5 to 45 MHz, which is unused for signal transmission television because of the addition of too much noise [22]. The bandwidth is allocated to subscribers by using time division multiplexing.

The downstream part is divided in two parts:

- The data signals for Internet access are transmitted on the cable using Frequency Division Multiplexing. The signal from the providers occupies 550 to 750 MHz (approximately).
- The remaining bandwidth available (50 to 550 MHz approximately) is occupied by the television broadcast. Since each TV channel occupies 6 MHz band (Europe) [22], it is possible to accommodate more than 80 channels.

Figure 12 shows the HFC frequency bands to coaxial cable:

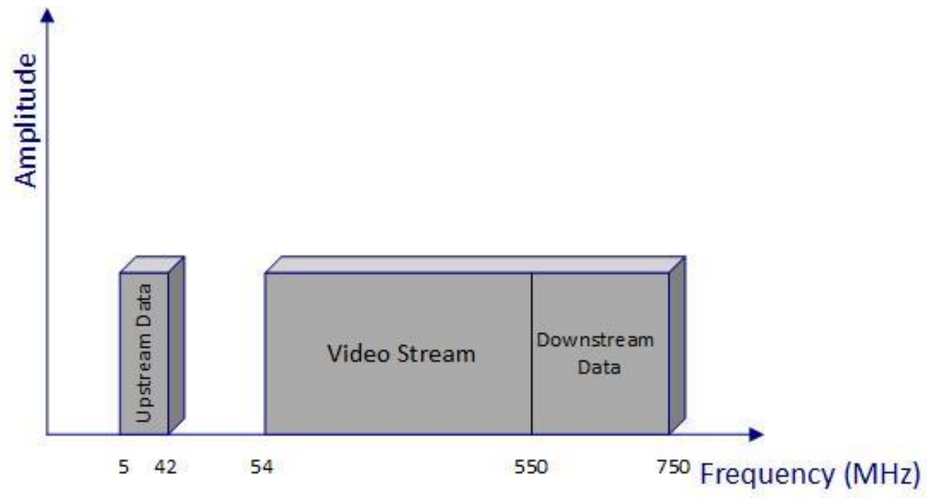


Figure 12 – HFC Frequency bands (coaxial cable) (Draw by the author)

Summarizing the main information transmitted between the Head End and the homes of the consumers is divided on these two directions:

- Downstream: contains information from TV, Voice and Internet;
- Upstream: contains the controls of set-top boxes, modems or monitoring signals from the amplifiers, Voice and Internet.

3.3 HFC - Detailed Structure and Equipment

HFC networks use 2 types of physical connection: zones of coaxial cables and zones of fiber optic distribution for longer sections of the network.

The optic fiber provides very high transmission rates (speeds) per second (about 40Gbps), with low decay rate per kilometer, providing a high cost of material for its of implementation, making it ideal for deployments of long distances and large amounts of traffic. The coaxial cable is good for smaller distances and larger areas of dispersal, despite having less speed and capacity compared to the fiber, but has lower costs. Compared to other copper conductors is more protected against magnetic interference, reducing the effects and external signals about the signals to be transmitted.

The following picture 13 shows the coverage area of optical fiber and coaxial cables:

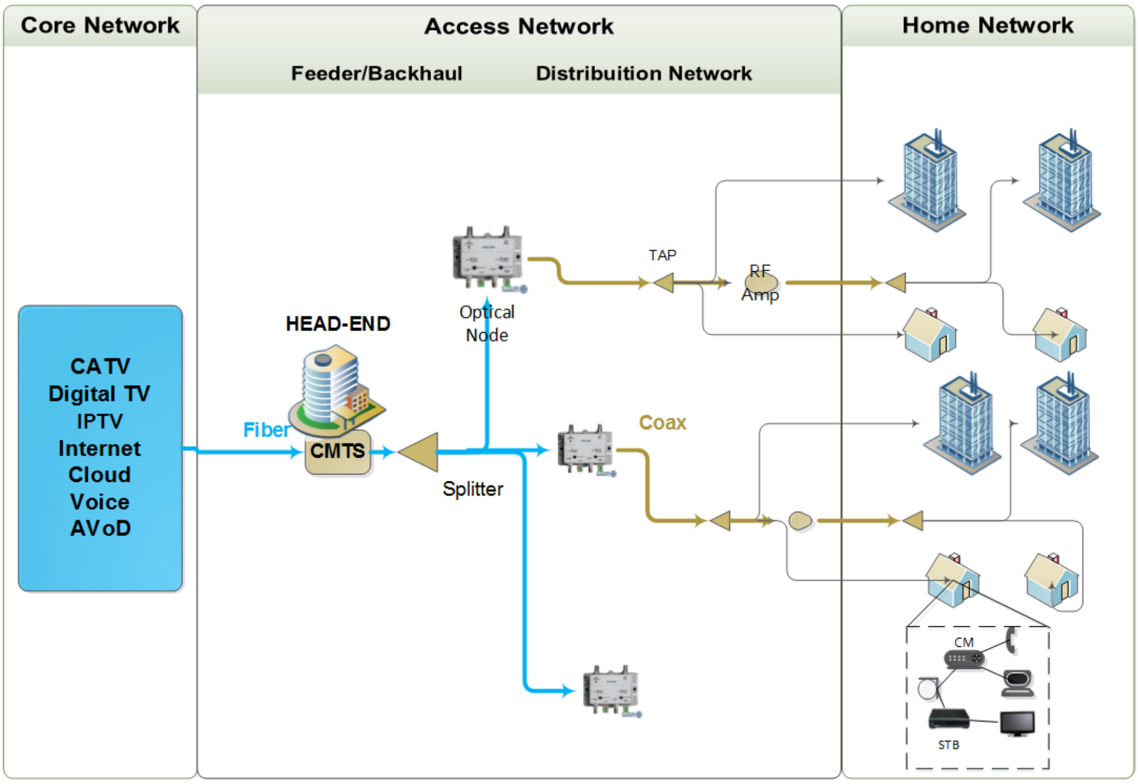


Figure 13 – HFC Structure (Draw by the author)

The elements of this architecture are:

- Head-End (CMTS - Cable Modem Termination System) and Regional Sub-End;
- Cabling, ducts, cabinets, drop cables, physical connectors: (Fiber and Coax);
- Optical Node (ON) near homes;
- Line RF Amplifiers;
- Splitters, Taps and Power Splitters;
- User Equipment (CM – Cable Modem).

The HFC network has the advantage of using existing passive infrastructure, implying lower implementation costs. But the sharing network model imposes limits in the bandwidth available for each user, so that if a large number of users connected to the network in simultaneously, smaller bandwidth will be available per user.

3.4 Equipment Organization and Cost Elements

The structure of HFC architecture is divided into three parts, the equipment in the Head-End and the distribution and feeder network (both on fiber or coax, including their conversion elements and equipment in the consumer's home).

To simplify the organization of cost elements, a group will retain the costs of optical equipment (equipment located in the Head-End and used in converting optical electric); another group is the distribution and feeder network of coax, which presents greater extend (area). Finally the last group will contain the cost of equipment used in the consumer's home.

The following figure 14 explains the organization and sequence of the elements of a HFC network, along with its group division:

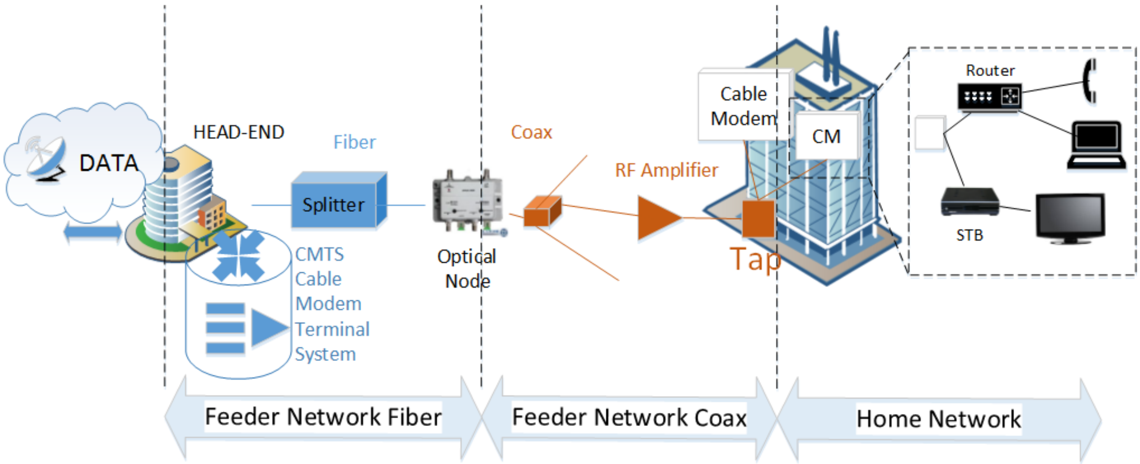


Figure 14 – Sequential Elements on HFC Network (Draw by the author)

4. HFC Access Network Dimensioning

For the implementation of a new HFC access network, it is important to address several key aspects to your dimensioning:

- equipment capacity and granularity;
- power budgeting over the network;
- dealing with spatial uncertainty associated with geographical and demographic different areas;
- dealing with the consumption of bandwidth users, avoiding overloading the network;

4.1 HFC Network Dimensioning

The Head-End is the entry point for all information conveyed in a HFC network, like the content of Broadcast TV and Video on Demand (VOD) received by satellite, which are then multiplexed and transmitted by stream in real time through a multicast protocol.

The Head-End includes also the CMTS, equipment that takes data received from internet and sends it together with the audio and video signals. The CMTS is always in contact with the CM in each customer premise allowing provide service and used to aggregate traffic between the two modems. The structure of a Head-End uses several different components used as it is shown in the following figure 15 [31]:

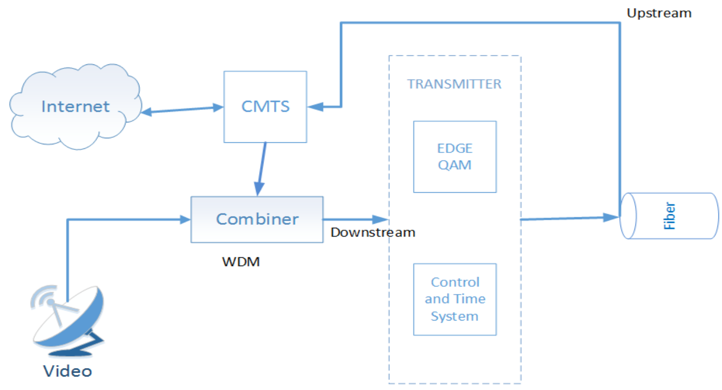


Figure 15 – Head-End Structure (Draw by the author)

To explain the granularity of the components of Head-End, each element has capacity for a number of subscribers. In figure 16 is described this granularity by a hierarchical tree:

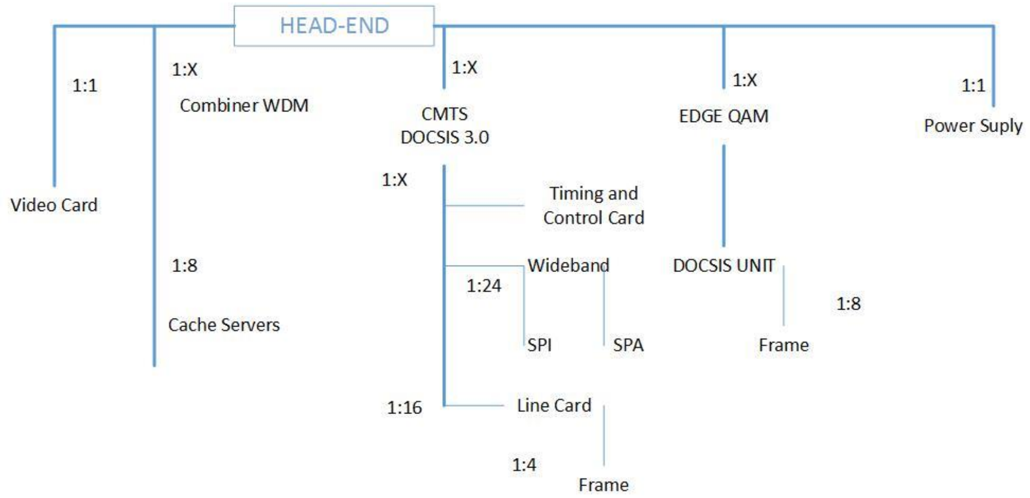


Figure 16 – Granularity tree structure of a Head-End (Draw by the author adapted from [31])

After leaving the Head-End, the signal spreads over optical fiber and is divided by optical splitters over the line until it reaches the Optical Node in some cabinet near the user's home or other sub Head-End.

The figure 17 shows an example of one Optical Node:

Figure 17 – Example of one Optical Node - Model OTMN-II High Performance 4-Port Outdoor Optical Node [26]

In the Optical Node the optical signal is converted to electrical and is afterwards sent through a forward-path and over coaxial cable to the user's home. The same coaxial cable includes also a return path between the house and the Optical Node. The signals that are divided through the power splitters (TAP) are electric and suffer attenuation when propagating along the coaxial cables, so to avoid losses RF Amplifiers (bidirectional) are implemented over the lines to convert the low-power radio-frequency signal in to larger signal of significant power [27]. The tap is used to distribute or combine signals from RF (Radio Frequency). The figure 18 illustrates an example of a TAP and a RF Amplifier implemented:

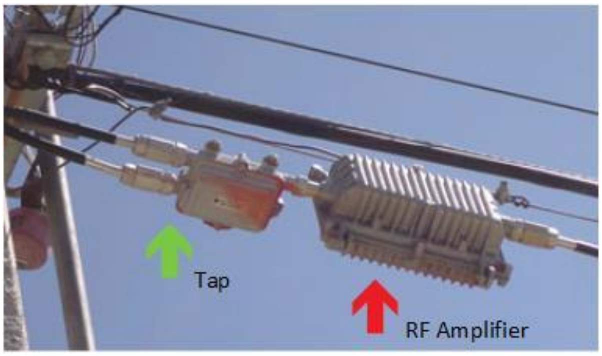


Figure 18 – Example of a Tap and RF Amplifier installed [28]

Finally the signal reaches its final "destination" the drop network. Here the signal is demultiplexed and split to the Cable Modem (Internet and VoIP) and Cable Box (STB).

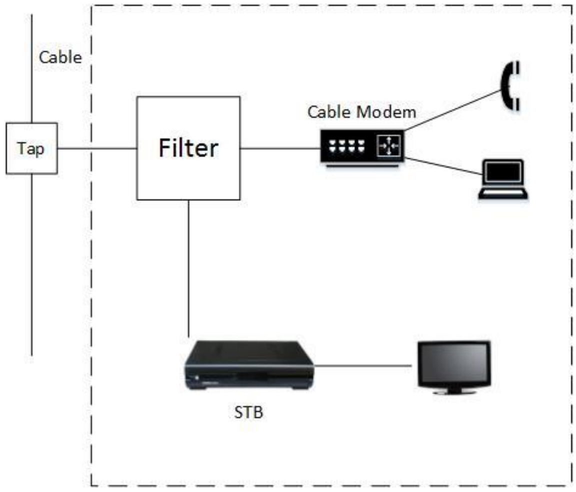


Figure 19 – Drop Network (Draw by the author)

4.1.1 Equipment Ratio

To better understand the components and the ratio amounts needed in a HFC network to cover a number of subscribers, a table 3 is presented below:

HFC				
Network Place	**Equipment**		**Technical Features**	**Ratio**
Head End	Racks	Rack	42 U	42
		Subrack	4 U	4
		Subrack per rack	42/4	10
	RF/WDM PATCHCORD (10 m)	RF/WDM Ports	128 ports	128
		RF/WDM (128OUT)		-
		RF/WDM Rack	Capacity to 128 ports	128
		PC OLT-WDM	1 to connect for each port	1
		PC RF-WDM	1 to connect for each port	1
	RF/WDM TRANSITION MODULE	PC WDM-TRANSITION	1 to connect for each port	1
		TRANSITION MODULES		1
		subrack TRANSITION MODULE	24 transition modules/subrack	24
	Edge QAM Device DOCSIS 3.0 CMTS DOCSIS 3.0	Bastidor	-	64
		Unit	-	64

		Bastidor	-	64
	Control System	Line Card	-	64
	Edge QAM Device DOCSIS 3.0	Wideband SPI	-	64
	Edge QAM Device DOCSIS 3.0	Wideband SPA	-	64
		Timing and Control Card	-	64
	Cabinet (SRO)	Optical Node (NOT)		288
Distribution / Feeder Network	Distribution ODF Passive Splitting	Distribution RF Amplifier		16
		Splitter 24		24
		Splitter 48		48
		Splitter 98		96
		Tap 1:4		4
		Tap 1:8		8
		Tap 1:16		16
	Distribution Wiring	96 optical fiber		96
		Joint (JFO) 96 o.f.		96
		Coax 8		8
		Joint (JC) Coax 8		8
		96 optcal fiber		96
		48 o.f.		48
		24 o.f.		24
		12 o.f.		12
		24 o.f.		24
		12 o.f.		12
		8 Coax		8
		2 Coax		2
Drop Network	Drop Building	TAP 4		4
		TAP 8		8
		Cable Coax 2		2
		Cable Coax 8		8
	Drop Client	Router		1
		Telephone IP		1
		Cable Modem		1
		Terminal STB		1

Table 3 – HFC elements

4.1.2 Equipment Costs

Using information taken from the article "Base de Dados de Elementos de Custo HFC", and described on Appendix B. The following section shows a better understand of these costs and their evolution.

4.1.2.1 Price Evolution

As it is known, the equipments monetary value decreases over the years. This decrease depends on various factors, such as the purpose of the material, the age technological implementation speed, among others. To have closer equipment values to the actual ones over the years, we have the following equation 1: [13]

$$P(t) = P(0)\left[n_r(0)\,.\,\left(1 + e^{ln\left[\frac{1-n_r(0)}{n_r(0)}\right]-\left[\frac{2\ln(9)}{\Delta t}\right].t}\right)\right]^{\frac{\ln(K)}{\ln(2)}} \quad (1)$$

where,

P represents the price of the equipment along *t* years;

n_r represents the technological age;

Δt represents the speed of implementation;

K represents the class type of equipment (purpose).

The different purposes of the equipments are listed on table 4:

Purpose	K value
Advanced optical components	0,7
Passive optical components	0,8
Optical Cables	0,9
Electronic components	0,8
Coax Cables	1,0
Building	1,0

Table 4 – K values for different king material purpose

About the production rate of any equipment, the different deployment speeds and technological ages are present on the next table 5 and 6:

Class	Value Nr(0)
Old	0,5
Mature	0,1
New	0,01
Emergent	0,001

Table 5 – Classification of components on the deployment speed

Class	Value Δt
Very Fast	5
Fast	10
Slow	20
Very Slow	40

Table 6 – Classification of components over the age of technology

Using the initial prices and applying the formula 1, the result of price evolution is presented the table on Appendix B.

4.2 Services

In HFC networks it is possible to transmit video, audio and Internet services. The service offered to customers is the triple play, including VoIP, high speed internet and IPTV, as shown in Figure 20:

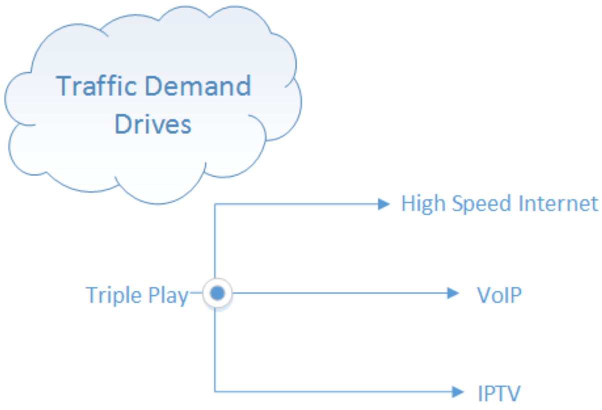


Figure 20 – Triple play figure (Draw by the author)

The bidirectionality of the distribution network and the cable modems in customer's houses allows the use of interactive systems, such as Internet access, VoIP and Interactive Television (Triple play).

4.2.1 Spectrum Organization

Some of HFC features are the wide frequency spectrum that the existing cable infrastructure can carry over long distances, and the shared medium which results in natural broadcasting capabilities.

In the downstream the available bandwidth has 33 channels of 6 MHz, but HFC equipment typically has more than 33 subscribers. For this reason the channels must be shared among a group of subscribers. We have the possibility to broadcast in multicasting. Each subscriber has a specific address registered. The cable modem for the group finds the recipient address that was assigned to the provider and makes the delivery to the subscriber, all other data which does not matched is discarded.

Multicasting is the delivery of information to multiple recipients simultaneously using the most efficient strategy [29]. Messages will go through a link only once and the messages are duplicated only when the link is divided into two distinct directions. The next figure illustrates the multicasting model:

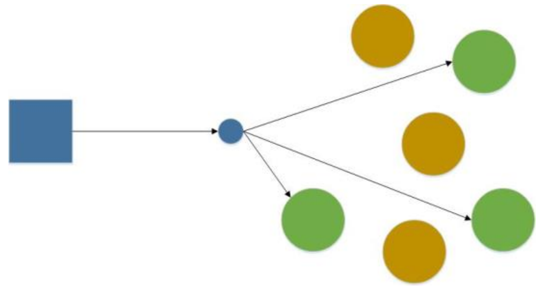


Figure 21 – Multicasting Model – green balls served (Own Development)

The upstream bandwidth is only 36MHz, with just 6 channels of 6 MHz available. A subscriber needs a channel to send data to the Head-End, so to share these channels to a high number of subscribers HFC. FDM (Frequency Division Multiplexing) is required to divide the bandwidth between subscribers that must be of the same neighborhood. The service provider allocates channels dynamically to each group of subscribers which dispute the available channel to start the transmission, if another subscriber in the same group wants to transmit, he has to wait until the channel be available.

The figure 21 shows how FDM works:

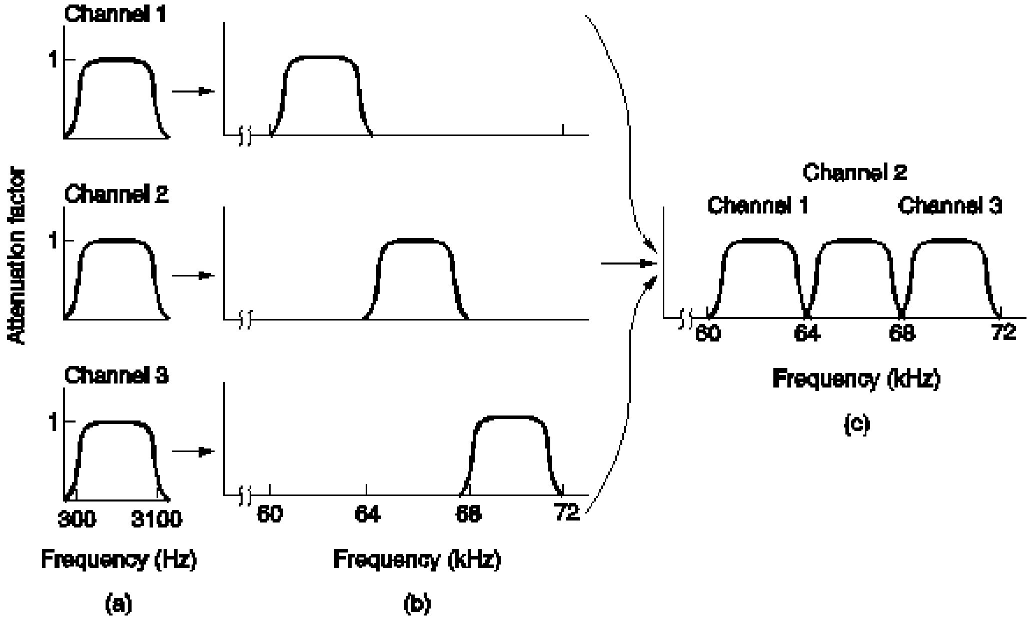


Figure 22 – FDM example – (a) Original Bandwidths; (b) Bandwidths raised in frequency; (c) The multiplexed channel [30]

4.2.2 Link Budget

Link budget is a way of quantifying the link performance, taking into account the loss and gain of every element of the link applied on the transmitted signal. The launch power is the power injected by the transmitter and the received power is known as the receiver sensitivity.

The safety margin covers unavoidable variations of the several components characteristics and other malevolent effects, and its standard value for safety margin is 3 dB [31]. This value will assure that the link is still safe to a certain extent, but it will be advisable to give a special attention to the choice of its element.

The simple link budget equation is:

$$Receive\ Power_{(dBm)} = Transmitted\ Power_{(dBm)} + \ Gains_{(dB)} - \ Losses_{(dB)}; \qquad (2)$$

So a link budget is the sum and total of all gains and losses in the signal connection between two parties from end to end, changing the above formula:

$$Prx = Ptx - Ltx - Lfs - Lm - Lrx + Gamp; \qquad (3)$$

where:

Prx = received power (dBm);

Ptx = transmitter power (dBm);

Ltx = transmitter losses (fiber, coax, connectors...) (dB);

Lfs = free space loss or path loss (dB);

Lm = miscellaneous losses (fading margin, body loss, polarization (dB);

Lrx = receiver losses (fiber, coax, connectors...) (dB);

Gamp = RF amplifiers gain (dB).

Note: No gains or losses associated with antennas are taken into account because they do not exist in HFC network.

4.3 Geographical and Demographic analysis

The methodology used in this work is an adaptation of the methodology used in the following document [32]:

Duarte, A. Manuel de Oliveira, "Metodologia de classificação de áreas geográficas para efeitos da análise tecno-económica de projetos de investimento em redes e serviços de telecomunicações", Universidade de Aveiro, 2011.

The geographical features are very important in the construction and design of a new telecom access networks. The distribution of users homes and buildings have a direct impact on the cost of physical connection, since as in the competitive dynamics between the services they influence the profits obtained.

For a geographic and demographic study the aspects to have into account are population density, coverage area, population distribution, type of buildings to cover and financial capacity of the local habitants. With these data we can organize and measure the most inexpensive and effective implementation of a new access network. To get a correct assessment, detailed information on the population of a particular region is required. That way, determining market clients and services that we offer through the needs and capacities of that specific area, it is possible identify the proper technology to be applied and its cost.

After knowing the type of population, it's needed to study the present different types of urban morphology organization [33]. Figure 23 shows the geometric model to characterization urban areas:

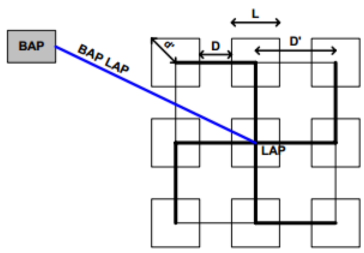


Figure 23 – Geometric Model to Characterization of Urban Areas - Cluster Methodology [34]

On either rural or urban environments, the demographic morphologies can be divided in 4 situations based on 2 factors: distance and dispersion, as figure 24 illustrates [35]:

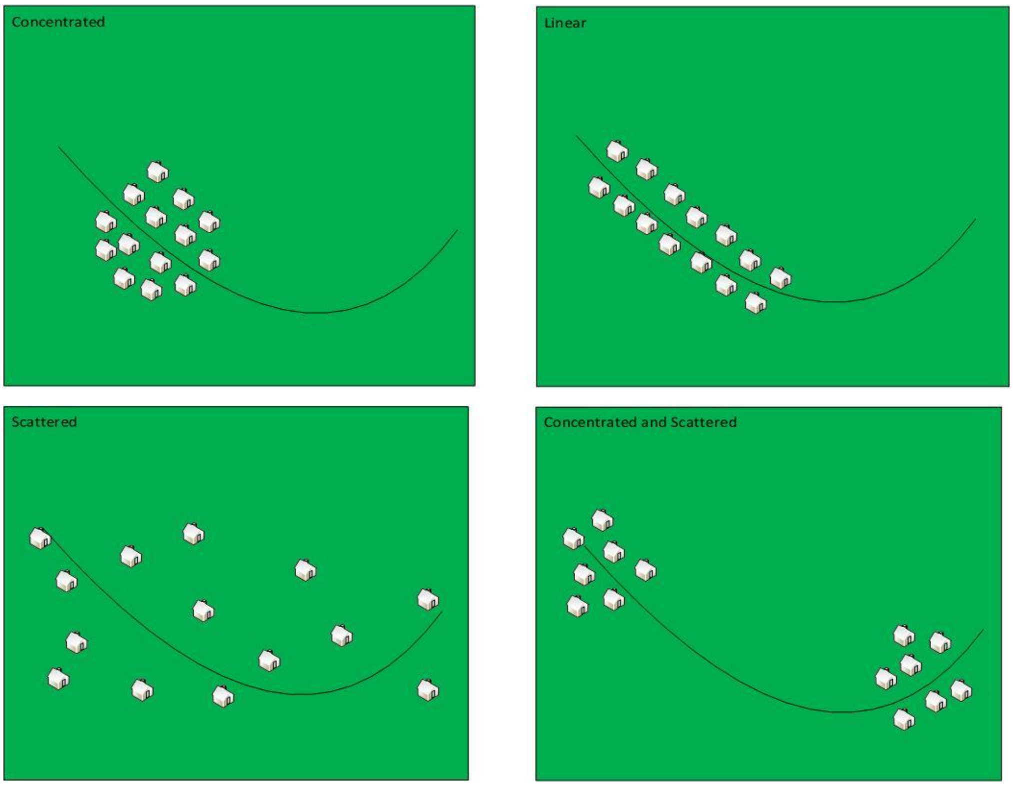


Figure 24 – Different building morphology for the same population density (Adapted from [32]

For a techno-economic analysis, it will be necessary to know how to cover the population geographic distribution, being impossible to take an overall value of this distribution, an estimation can be made through mathematical functions and graphs, allowing strict conclusions about implementation and cost of a new access network, achieving a more complete area coverage.

4.3.1 Population Distribution

There are different ways to estimate population distribution and some of these methods are described on the following sections.

4.3.1.1 Uniform Distribution

Called a "perfect world" in telecommunications, if the uniform distribution population is, as the name states, a population is distributed evenly through the area to cover. The calculation process would be simple and the costs would be low [36]. Figure 25 illustrates a uniform distribution with a centered HE:

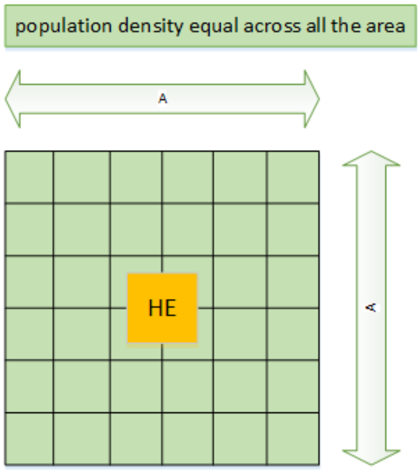


Figure 25 – Uniform Distribution on a square with side A with a centered Head-End

In another hypothesis, the Head-End is placed not in the center of the area, but in one end, serving square area from one edge. This way, the client would be at a distance between 0 and 1 (A), with a population density uniform. The figure 26 represents a uniform distribution on an area with cornered HE:

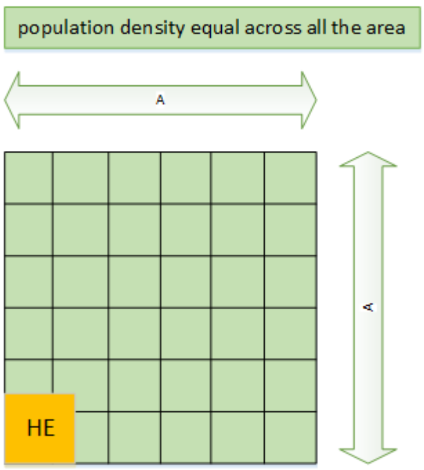


Figure 26 – Uniform Distribution on a square with side A with a cornered Central Office

The population was concentrated at a distance from the Head-End equal to the average distance [36]. Given the value of the area of the respective side of the square, the maximum distance of the user house, would be:

$$h^2 = A^2 + A^2 \Leftrightarrow h = \sqrt{2A^2} \Leftrightarrow; \tag{4}$$

$$\Leftrightarrow h = A\sqrt{2}; \tag{5}$$

The following figure 27 shows the mathematical trigonometric relations to calculate the average distance from a house to the cornered HE:

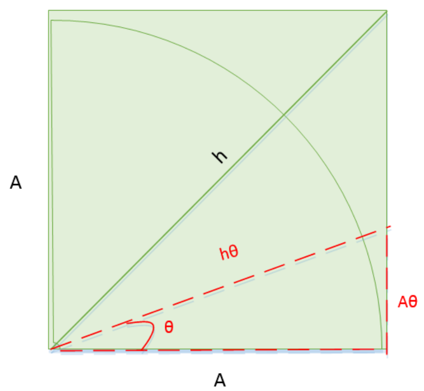


Figure 27 – Trigonometric relations

Assuming an average distance from the Head-End to average home, the angle θ is given by[36]:

$$A\theta = h\theta \sin\theta; \tag{6}$$

Where the trigonometric reasons described above imply, θ ϵ [0; π/4]. From the analysis of the figure 27 above and the formula, there is [36]:

$$h\theta = \sqrt{A^2 + A^2\theta} = \sqrt{A^2 + h^2\theta + \sin^2\theta} \Leftrightarrow; \tag{7}$$

$$\Leftrightarrow h^2\theta = A^2 + h^2\theta \sin^2\theta \Leftrightarrow h^2\theta(1 - \sin^2\theta) = A^2 \Leftrightarrow; \tag{8}$$

$$\Leftrightarrow h\theta = \frac{A}{\cos\theta}; \tag{9}$$

Then the average distance is:

$$< L > = \frac{h\theta}{2} = \frac{A}{2\cos\theta}; \tag{10}$$

Considering the result of A from equation 10, it is possible to obtain the average distance to the Head-End in the direction of θ. It is necessary to calculate the average of all the angles θ, using the integral of equation 11 and the following developments of formulas 9 and 10.

$$\frac{1}{\pi/4}\int_0^{\frac{\pi}{4}}\frac{A}{2\cos\theta}d\theta=\frac{A}{2}.\frac{1}{\pi/4}\int_0^{\frac{\pi}{4}}\frac{1}{\cos\theta}d\theta=\frac{2A}{\pi}\ln\left[\frac{1+\sin\theta}{\cos\theta}\right]_{\theta=0}^{\frac{\pi}{4}}; \quad (11)$$

$$=\frac{2A}{\pi}\ln\left[\frac{\left(1+\frac{1}{\sqrt{2}}\right)}{\frac{1}{\sqrt{2}}}\right]-\ln\left[\frac{(1+0)}{1}\right]=\frac{2A}{\pi}\ln\left[\frac{\left(1+\frac{\sqrt{2}}{2}\right)}{\frac{\sqrt{2}}{2}}\right]=\frac{2A}{\pi}\ln\left[\frac{\left(1+\frac{2}{\sqrt{2}}\right)}{1}\right]= \quad (12)$$

$$=\frac{2A}{\pi}\ln\left[\sqrt{2}+1\right]\approx 0{,}561.A \quad (13)$$

Knowing that <L> = 0.561*A*, for a scenario in which the population is evenly distributes a square area of side *a*, it is possible to calculate the average distance from any client to the respective Head-End.

4.3.1.2 Not Uniform Distribution

The uniform distribution is not the most common current geographic models, because in reality the population gets distributed over a certain area. For a more realistic scenario is presented mathematical function (Poison Process) is used to define non-uniform distributions.

The Poisson distribution is based on a probabilistic method that grounds their probabilities in a process given by:

$$P_\lambda(r)=\frac{(pt)^r}{r!}r^{-pt}; \quad (14)$$

Then the Poisson distribution has a mean and variance $\lambda = pt$ [37].

To perform the population increase as a function of the distance to the Head-End makes the next representation is applied:

$$P_\lambda(r)=\frac{(\lambda)^r}{r!}r^{-\lambda}; \quad (15)$$

where:

λ – Poisson Mean;

r – Number of Occurrences

The Poisson mean value is equal to the expected number of occurrences within a given time interval, so the value depends on the average time taken for the event to occurs. The following figure 28 represents the Poisson function:

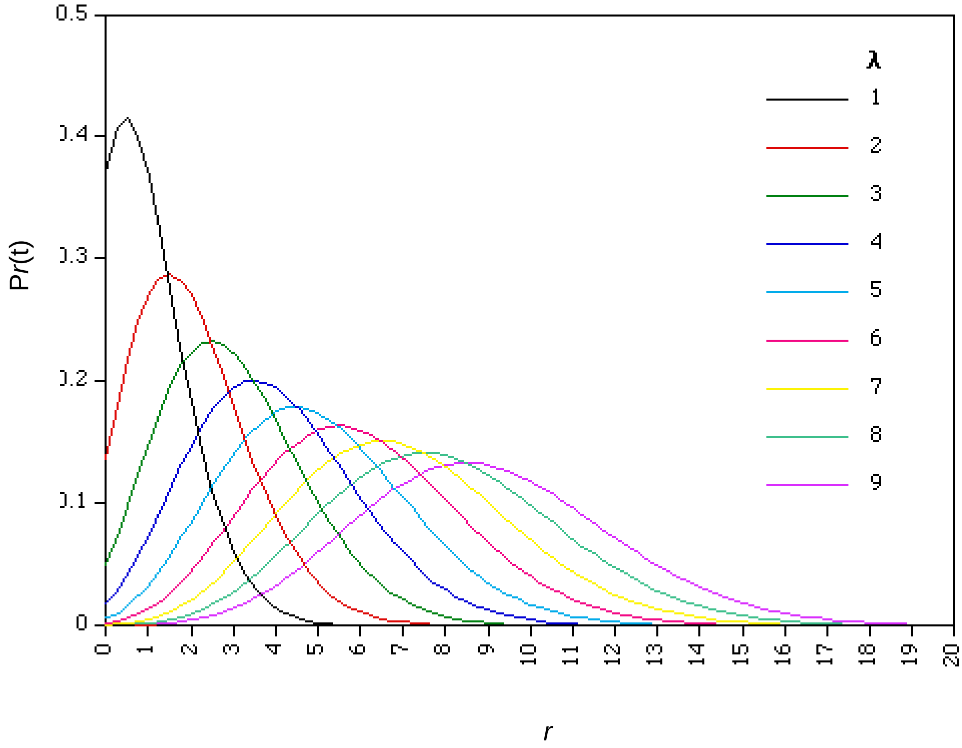


Figure 28 – Poisson distribution [37]

A cumulative function describing the probability of a given variable for a given distribution may be found, through:

$$P_\lambda(r \leq R) = \int_0^X P_\lambda(r); \quad (16)$$

And the cumulative function is graphical represented in the figure 30:

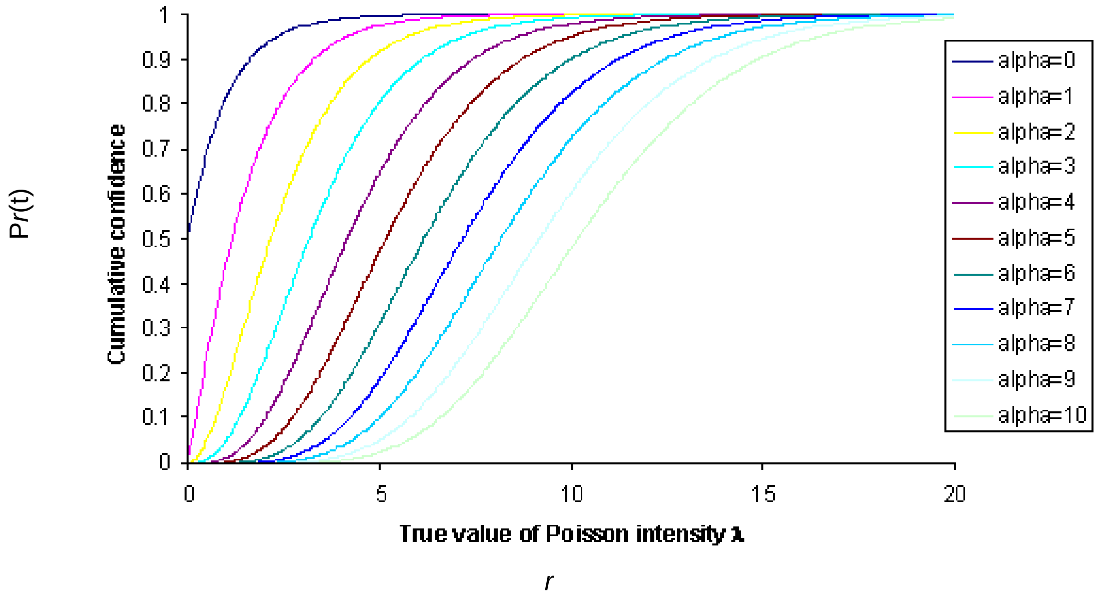


Figure 29 – Poisson Cumulative Confidence Distribution [38]

The Poisson process is widely used in other areas as telephone calls per time unit, accidents per time unit, defects per area unit red blood cells per area unit, etc.

4.3.1.2.1 The population near the Head-End

In this situation, as the name implies, the population density decreases with the distance to the Head-End, as represented in the next figure 30:

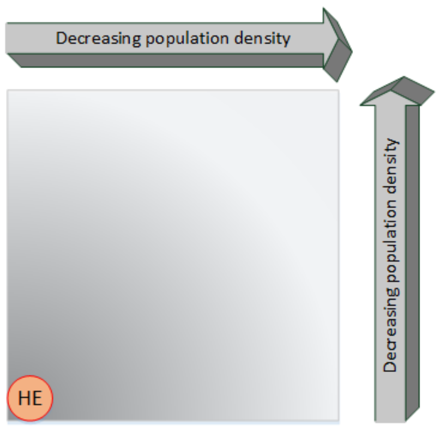


Figure 30 – Population density near from Head-End

Using the Poisson function and the integral calculus of it, it is possible to define the distance from the Head-End to the population average <L>, obtaining then an estimate of the wiring costs through the knowledge of the distance between HE and where half the population on to be served is contained:

$$\int_0^{<L>} 1 - P_\lambda(r \leq R) = \frac{Number\ of\ Consumers}{2}; \qquad (17)$$

To demonstrate the effects of this function, the following figure 31 presents a graph relating to a distance between 0 and 1, with the Poisson expected value equal to 13 and the number of potential subscribers is 50,000.

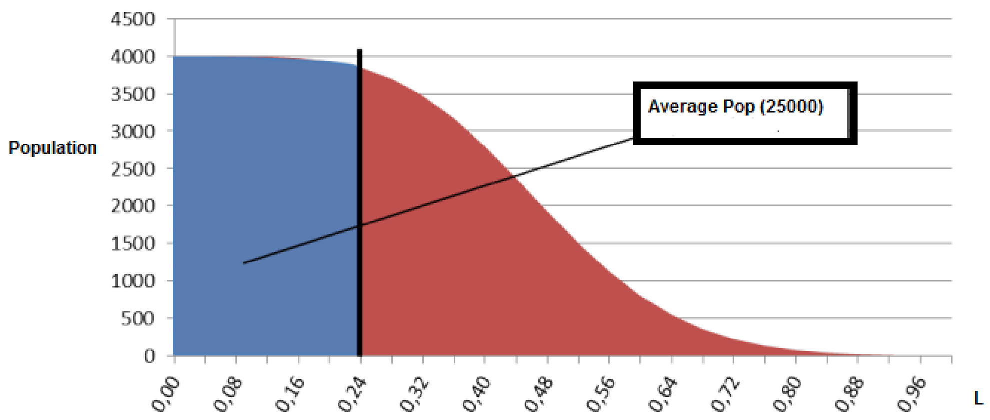


Figure 31 – Poisson Function with representation of average distance

Using the tool Microsoft Excel [40], the integral value of the distance to serve half the population (50000) is calculated. So the mean distance of the consumers houses to HE is <L>=0,21. As expected, the average distance is displayed below 0.5.

4.3.1.2.2 The population away from the central office

Unlike the method previously performed, it is intended that the density increases with distance to the HE, as shows the figure 32:

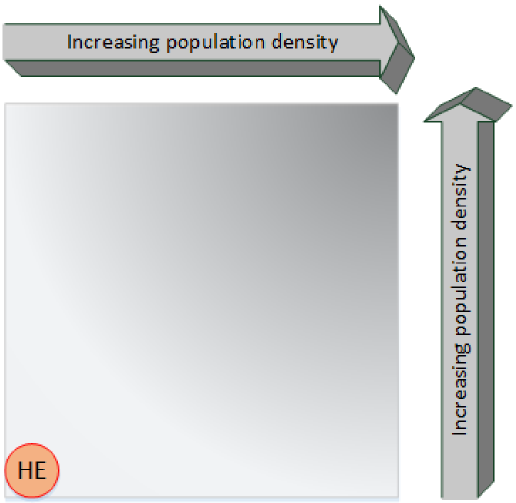


Figure 32 – Population density away from Head-End

Using again the Poisson and its integral calculation formula to get the average distance, the only difference is the inversion of probabilities, modifying the cumulative function.

$$\int_0^{<L>} P_\lambda(r \leq R) = \frac{Number\ of\ Consumers}{2}; \quad (18)$$

Following the method used above, the next figure 33 presents a graph relating to a distance between 0 and 1, with Poisson mean equal to 13 and 50,000 potential subscribers. Calculating the integral of the previous chart, to see when area is half.

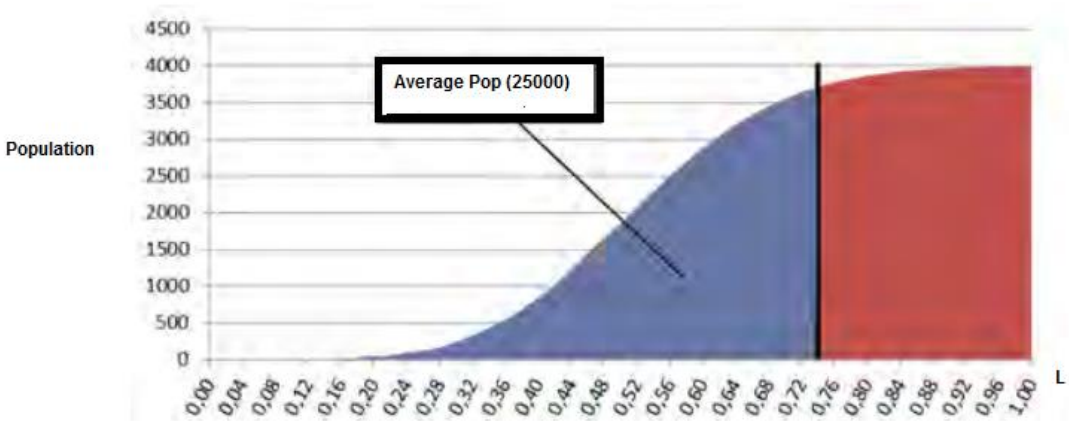


Figure 33 – Poisson Function with representation of average distance

The result shows that mean distance of consumers houses to HE is <L> = 0,75. As expected, the average distance is displayed above 0.5.

4.3.1.3 Gaussian distribution

When we need to calculate the average distance of the population where the highest density distribution is at an average distance from the HE, another hypothesis is used, the Gaussian distribution, as shown in the figure 34 and 35:

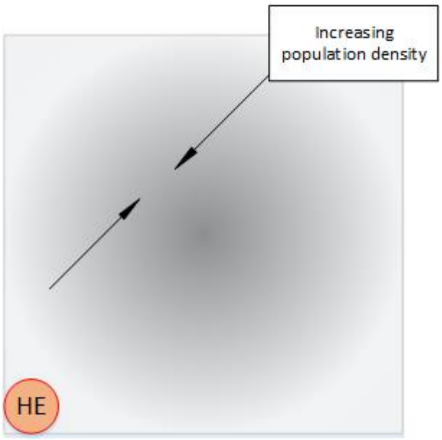


Figure 34 – Population density average distance from Head-End

Let's introduce the Gaussian formula and his respective graphic representation:

$$f(x) = N(\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left(\frac{(x-\mu)^2}{2\sigma^2}\right)}, x \in \mathbb{R}, \mu \in \mathbb{R}, \sigma > 0 \quad ; (19)$$

where:

μ represents the expected value;

σ^2 represents the variance.

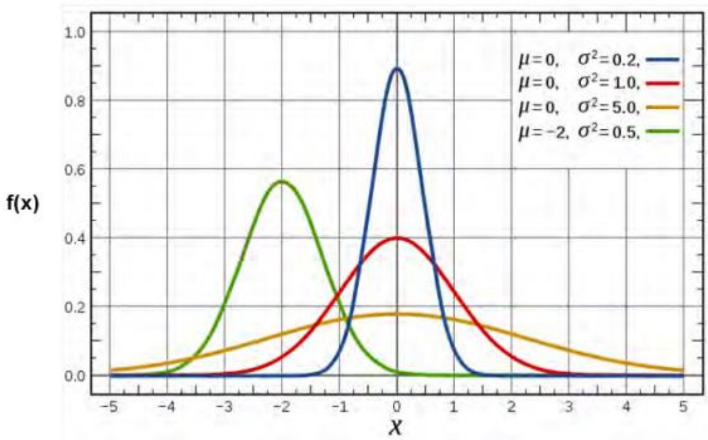


Figure 35 – Normalized Gaussian curves with expected value μ and variance σ2 [39]

In this case the greatest population density lie in a central square area selected for implementation, and the expected value is 0 and the variance is 1. Gets whether the formula:

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{(-\frac{x^2}{2})} \quad (20)$$

The formula described obtains the following graph, assuming 50,000 consumers as in the previous cases. Re-calculating the integral of the function, the desired average distance is obtained, equaling the value representing half of consumers. The value of the average distance is <L> = 0.5, as expected. The following figure 36 illustrates Gaussian distribution:

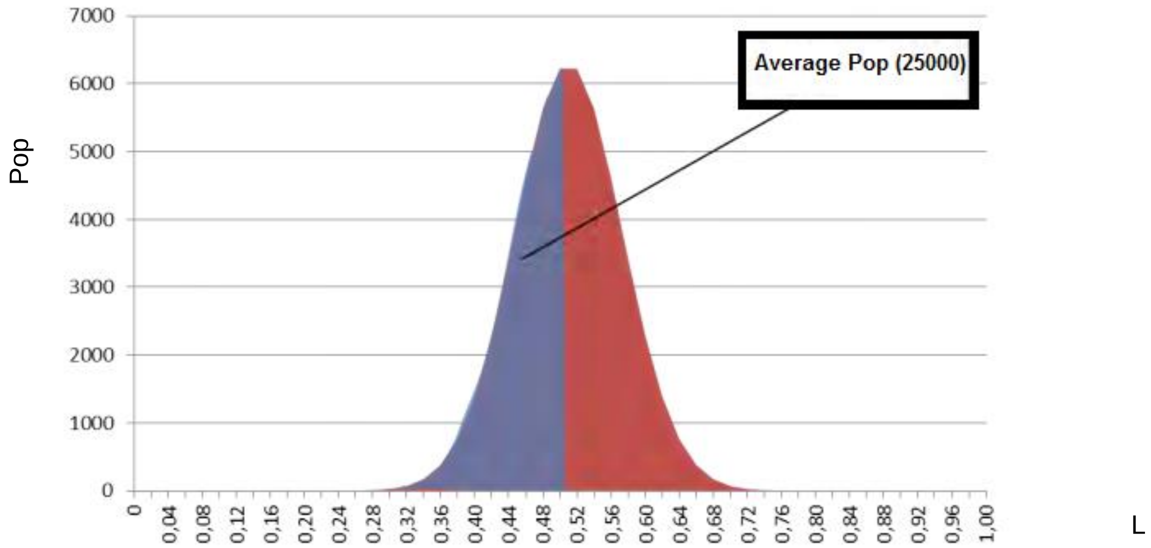


Figure 36 – Graphic representation of Gaussian distribution, with half Area colored (Average Population)

4.3.2 Characterization of scenario depending on their population density

The implementation of an access network is very important to determine the method of covering the homes of prospective subscribers with least expenses possible.

4.3.2.1 Study scenarios

As explained earlier in this chapter an area can be characterized by different types of population dispersion and models are used three types of morphologies:

- Urban area – the building morphology is concentrate and linear;
- Rural area – the building morphology is scattered;
- Suburban area – the building morphology is concentrate and linear in some parts while scattered in others.

Figures 37, 38 and 39 illustrate the building morphology for the different types of areas:

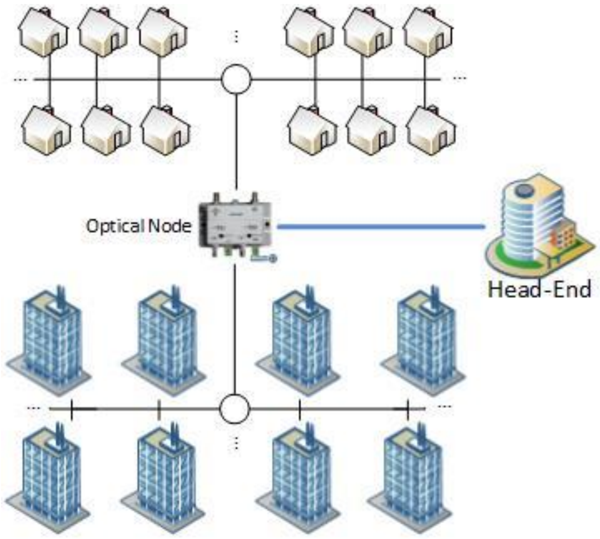


Figure 37 – Urban area example (Draw by the author)

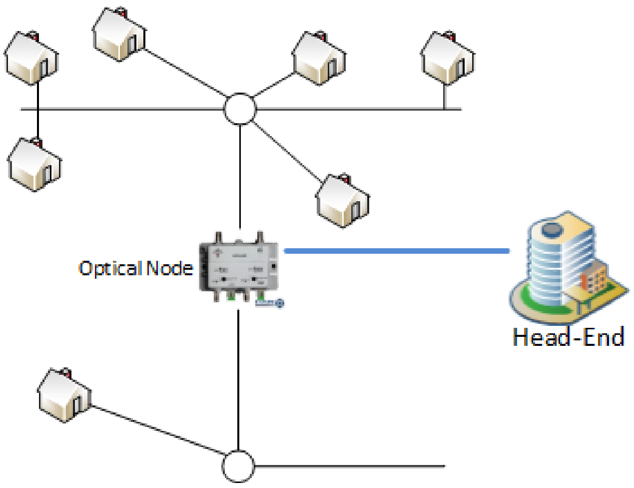


Figure 38 – Rural area example (Draw by the author)

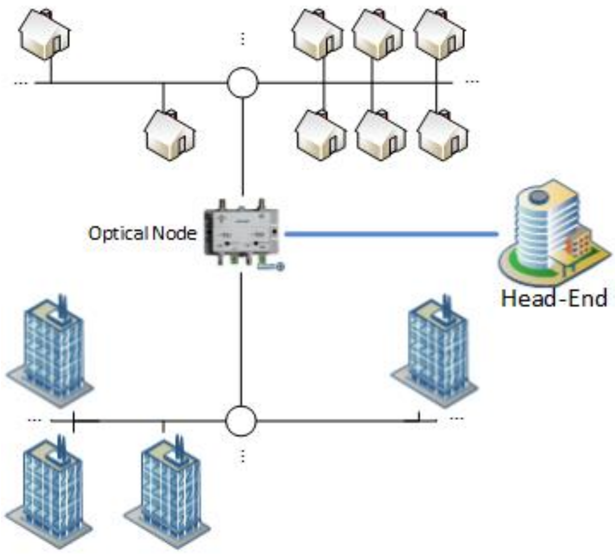


Figure 39 – Suburban area example (Draw by the author)

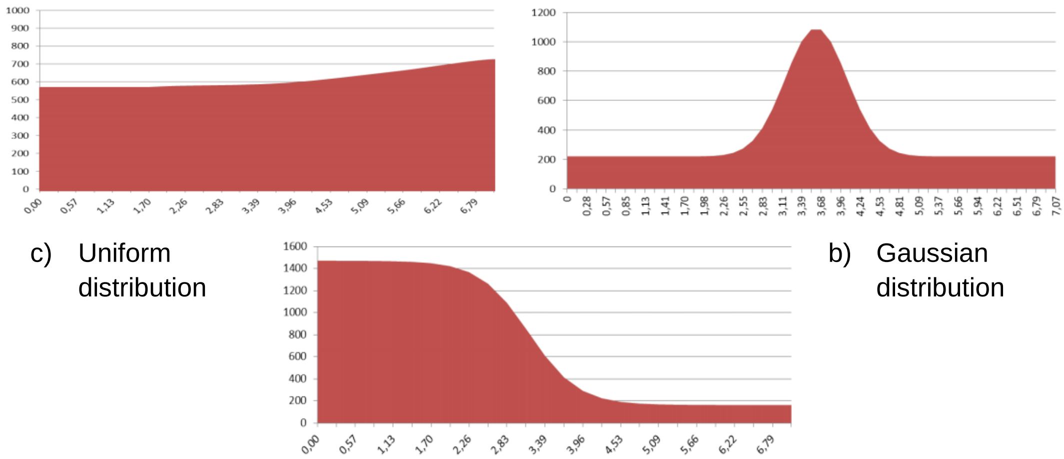
To initiate this study for different scenarios it is assumed that none of the regions have some kind of telecommunication infrastructure previously installed and as previously used the distribution loop is able to support all 25,000 subscribers, even if initially just a fraction of them adheres to the service.

Comparing the rural and urban cases, rural areas are characterized by lower subscriber densities, longer loop lengths, lower duct availability and therefore higher infrastructure costs when compared to urban areas. So there is an inherent flexibility in such investments, while the implementation in urban areas is faster and more profitable. Regarding the existence of various technologies and more service providers, the situation in urban areas where there is a high level of competition already present, requires the operator to act faster in order to get a competitive advantage against others operators. The suburban area shows the characteristics of two parts combined.

4.3.2.2 Population distribution by Scenario

To characterize each type of scenario mentioned above in relation to its population distribution in Figure 40 shows graphically the aspects mentioned below:

- Urban: most houses are buildings neatly built and the population distribution is uniform throughout the area covered;
- Rural: houses are dwellings arranged in a dispersed mode, the population distribution is Gaussian because the subscribers are at a distance relatively average Head-End;
- Suburban: is a model with more limited distribution than the urban one, more dispersed and the population density declined over it moves away from the center (Head-End)



c) Uniform distribution

b) Gaussian distribution

a) Near Head-End distribution

Figure 40 – Population distribution for different Scenario – a) Urban; b) Rural; c) Suburban

4.3.2.3 Assume Geographic Parameters

To creating an example with rigorous network dimensioning is important to define which population numbers characterize an urban, rural and suburban area, using the US Census Bureau definition [41], for developed environments (human settlements), the next table 7 provides an overview of the key reference values of each area:

AREAS	Homes per square km	Homes passed
Urban	5100	17500
Rural	120	6250
Suburban	1250	12500

Table 7 – Overview values of each area

Each cluster is a bundle from the Head-End, and represents also an occupied portion of the total area in the format of a rectangular grid. The length of the distribution network is calculated taking into account data on cluster area, aspect ratio and housing density [42].

4.3.2.3.1 Costs per Home Passed

The costs explained in this section correspond to the expenditures to cover all houses in the area, irrespective of their adherence. Capital costs include equipment (i), distribution (ii) and construction (iii) costs of the network.

i. Equipment

The values of this topic are presented on Appendix B and only taking into account the sum of the costs of all the equipment that is implemented in Head-End to cover the number of Houses Passed, it is possible to complete the following table 8:

Equipment		Price
Racks	Rack	720,50 €
	Subrack	89,50 €
RF/WDM	RF/WDM Ports	691,23 €
Edge QAM Device DOCSIS 3.0	Frame	14.400,00 €
	Unit	
CMTS DOCSIS 3.0	Frame and Line Card	25.920,00 €
	Wideband SPI	
	Timing and Control Card	

Table 8 - Head-End Equipment Price

ii. Distribution

About the distribution network, the area size and dispersion of the houses are the most important concerns. The prices of the distribution elements are also on Appendix B, and the next table 9 shows the price of them as a function of length.

Equipment		Price	Length
Wiring	288 optcal fiber	3.914,42 €	(km)
	96 optcal fiber	1.725,71 €	(km)
	48 o.f.	1.027,01 €	(km)
	24 o.f.	690,29 €	(km)
	12 o.f.	534,55 €	(km)
	6 o.f.	484,04 €	(km)
	1 o.f.	294,63 €	(km)
	8 Coax Cable	7.000,00 €	(km)
	2 Coax Cable	7.000,00 €	(km)

Table 9 - Wiring Equipment Price

Wiring cable length calculations: To the fiber cable length is determined according to the chosen distance between the Head-End and the average population distribution. As for the coaxial cable and respective ducts, the values are given by the TONIC model, shown on Appendix C. The next table 10 shows the wiring length calculated:

Area	Fiber Length (km)	Coax Length (km)
Urban	4	17,25
Rural	30	28,125
Suburban	8	25

Table 10 – Wiring Length

iii. Construction

As mentioned earlier these are the heaviest costs in implementing an access network. The wire deployment can either be underground or aerial. The underground way usually requires trenching, the price of labor work is expensive and some streets are historical or cannot have construction. Anyway the price of trench depends on the type of terrain and the length of the course until reach all homes [43].

The aerial mode is cheaper and requires poles, to implement new poles, it is necessary to labor on streets action that present prices close to the ones of trenching method. If is chosen to use poles already implemented, it is important to check the existence of free space, so that the cable can be strung on the pole [44]. Other costs to be considered are the manpower for activities not previously mentioned before, such as splicing, joint, sheath and enclosures. The next table 11 represents the labor costs from Appendix B:

Equipment		Price
Labor	Install cable p/ km	1.026,00 €
	Prepare cable p/ km	75,00 €
	Install joint	78,00 €
	Install pole	220,00 €
	Fusion thermal	3,60 €
	Fusion mechanical	8,10 €
	Trench Rocky Terrain p/ km	100.000,00 €
	Trench Sandy Terrain p/ km	60.000,00 €

Table 11 – Labor Costs

4.3.2.3.1.1 Deployment Scenario

Performing the implementation of an HFC network in the different scenarios mentioned, the coverage of all houses in the different types of area (urban, rural and suburban) are represented in next figures 41, 42 and 43:

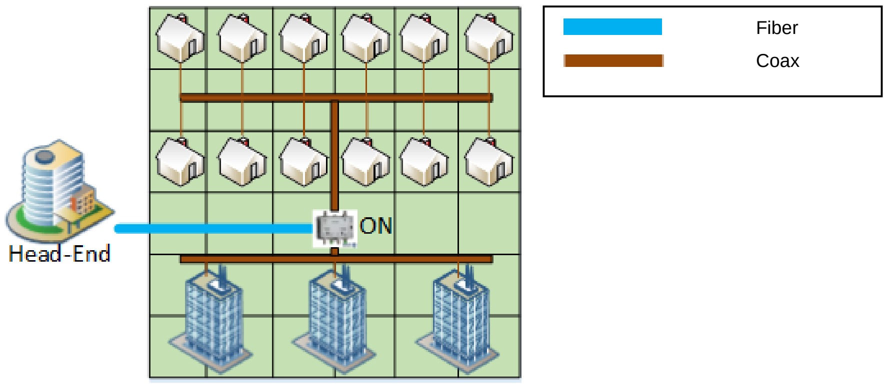


Figure 41 – Illustration of the Network Distribution in an Urban Area (Draw by the author)

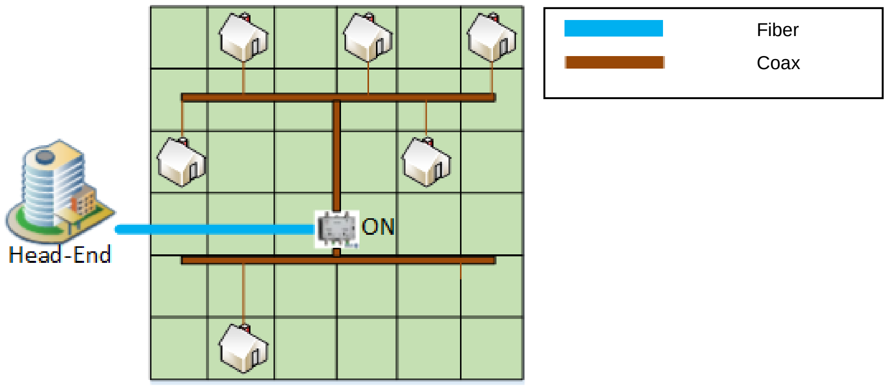


Figure 42 - Representation of the Network Distribution in an Rural Area (Draw by the author)

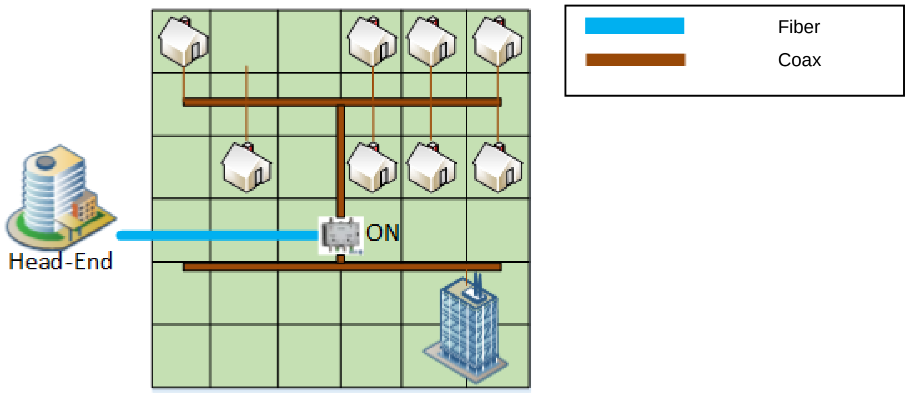


Figure 43 - Representation of the Network Distribution in an Suburban Area (Draw by the author)

4.3.2.3.1.2 Results

To not interfere with techno-economic analysis we assume here an example implementation absurd. Full implementation of the entire network in the initial year, to evaluate the capital costs per scenario. Taking into account the previously mentioned, it is possible to assume the following costs demonstrated in the tables 12 and 13 below:

Deployment					
Area	Size (Sq/km)	Houses	Num Clusters	Fiber Line (km)	Coax Line (km)
Urban	4	17250	27	4	17,25
Rural	52	6250	10	30	28,125
Suburban	10	12500	20	8	25

Table 12 – Deployment Values in different scenarios

	Costs			
	Equipment	Wiring	Construction	TOTAL
Urban Area	1.129.173,21 €	952.923,54 €	2.767.387,50 €	4.849.484,25 €
Rural Area	418.212,30 €	3.422.543,40 €	10.804.218,75 €	14.644.974,45 €
Suburban Area	836.424,60 €	1.381.048,61 €	4.227.750,00 €	6.445.223,21 €

Table 13 – Deployment Scenarios Costs

Now that the costs of covering all the houses in the area are known, the next graphs on figures 44, 45 and 46 show comparisons between the different scenarios and possible conclusions to draw:

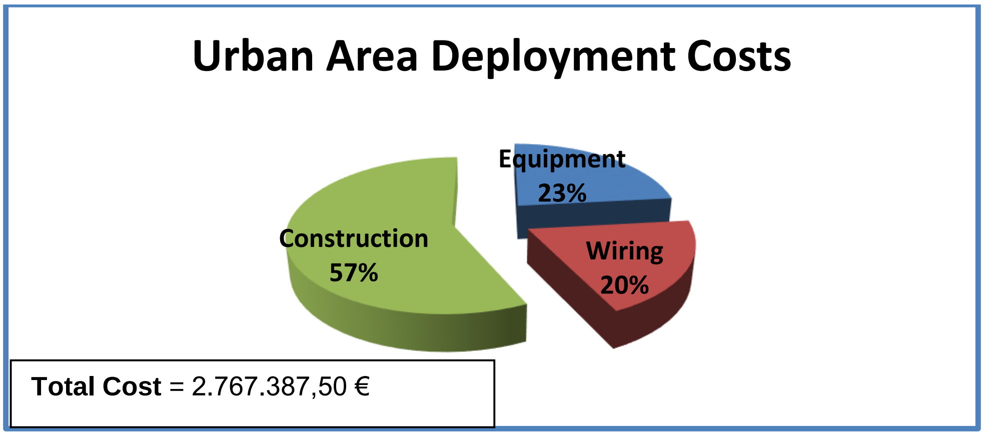


Figure 44 – Graphical representation of the percentages of the cost element for the Urban Area Deployment

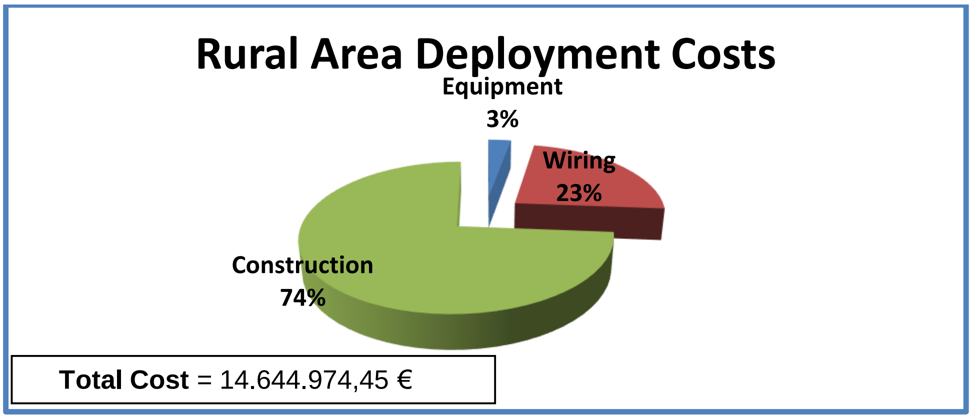


Figure 45 – Graphical representation of the percentages of the cost element for the Rural Area Deployment

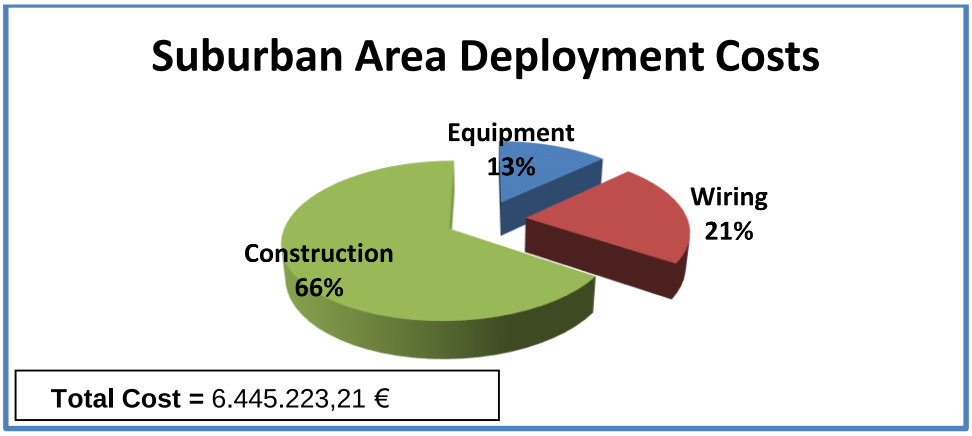


Figure 46 – Graphical representation of the percentages of the cost element for the Suburban Area Deployment

As it is possible to observe the most expensive element in the implementation of an access network is the means for building the distribution network, for all scenarios the labor costs are the great representative of more than half the total cost. This value increases with the increase of the area to be covered, without taking into account the type of ground trenching. The cost of trenching depends on the underlying bedrock. Also, in urban areas, restoring the sidewalks and front lawns are additional expenses.

Returning to the theme of this chapter and evaluating now only the capital costs per home passed, the next table 14 shows that values for each scenario studied:

	Cost per House Passed
Urban Area	581,13 €
Rural Area	2.343,20 €
Suburban Area	815,62 €

Table 14 – Cost per House Passed for the different Scenarios

4.3.2.4 Deployment Options

Comparing the different scenarios studied capital costs associated with the implementation of an HFC network on rural environment is very expensive, and the density of inhabitants per square how no guarantees of profit for implementing the network.

As it was shown before the higher costs are the construction and labor services. With a large area and a low population density, prices per home passed or served are proportional to these classes of implementation costs.

For the other two scenarios costs per house are good for the implementation of a project network long term, even with penetration rates below those used in the example (optimistic). It can be stated that with a higher population number in urban environment, additional equipment is required at the head-end (more costly).

Nowadays the cable TV and the internet became a practically mandatory good of society, so that people living in rural areas have the ability to require the same services available in areas with higher population density, and government agencies promote sufficient financial support for these investments and coverage of new access networks, allowing private companies to create profitable implementation projects for rural areas by reducing capital costs. This idea allows better access to information and multimedia content, encouraging industrial investment and avoids the depopulation of these rural regions.

4.3.2.5 Importance of Full Coverage

On these days the total coverage area of a given population and the capacity guaranteed for all users are vital pieces in all service provider companies. The bandwidth consumption importance is explained in the next chapter 4.2. About the service reach ability from all users in the area, it is important because when some consumer pretends to adhere to some Internet and Cable Tv service, it will not wait be required a waiting time until the service be available at his place of residence.

When a user wants to accomplish the adherence to a service, it checks the local services available and chooses the most advantageous, though given the confirmation of a more recent date of a new service release, he prefers something with immediate results, even if it has a lower quality or a higher price.

Evaluating this information, it is beneficial for a company to cover the greatest possible number of homes, even if the access is still small, guaranteeing more leeway for any immediate major penetration rates. To also avoid too high costs, the outsourcing of labor work should be performed the a less number of times possible, because large-scale constructions costs have diminished, compared small-scale constructions, not only to employees as in legalizing activities.

4.4 User's Bandwidth Consumption

The telecommunications network equipment can support a large number of users, but can only have one Head-End with a limited number of CMTS cover a large number of subscribers. The bandwidth must be engineered if the networks want to operate properly. The control solution is modeling data traffic (Data, Voice and Video), so that it's possible to predict how many cable modems the network can support.

4.4.1 Failures and Low Speeds Transmissions

The next figure shows the tragic cycle of a service provider when the available bandwidth is not able to cover all users in the area adherent.

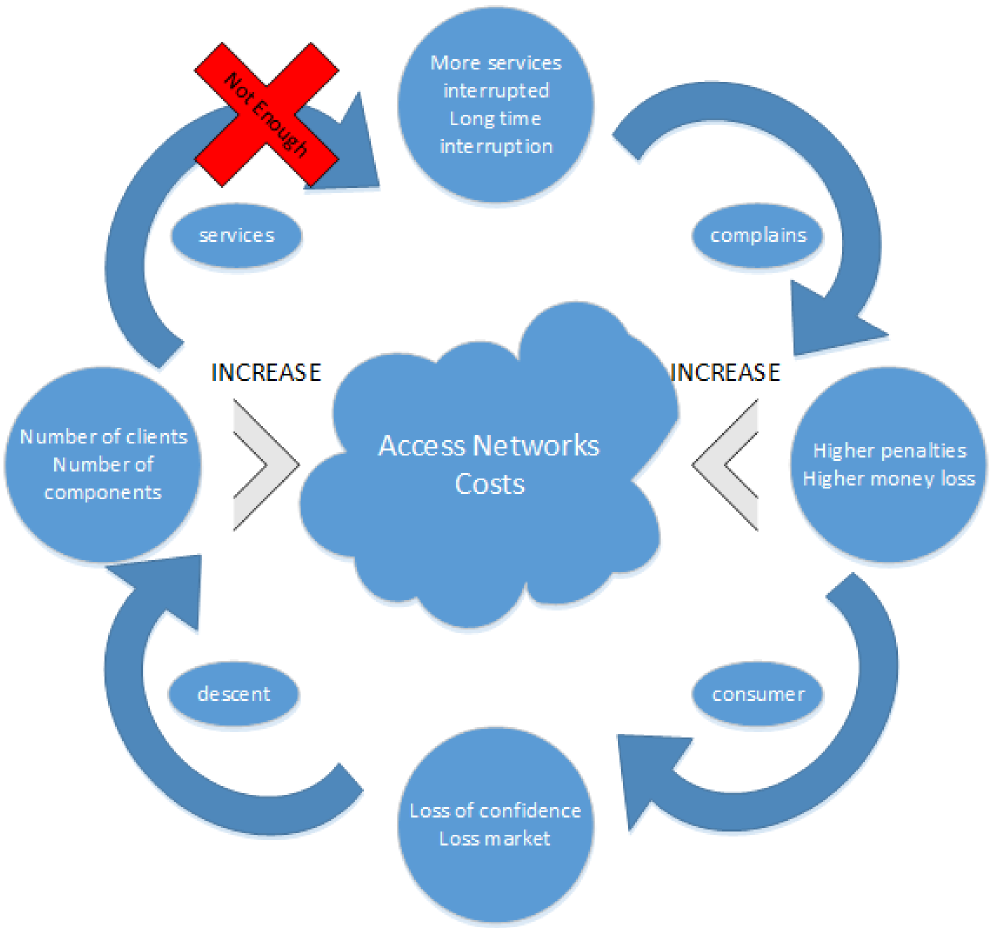


Figure 47 - Services Failures or Low Speeds Transmissions (Draw by the author)

Failures in telecommunications services are a plague. Today's society is very curious and discloses too much information about personal life, people talk about all services they have and a dissatisfied person will pay more attention to the censures and try to change service if someone proves to be more satisfied with another service. We're so used to instantaneously access in all type of data, that several delays or interruptions on service leads to a profound complaint.

Secondly, when someone reveals interested in acquiring or entering in a new model of telecommunications service available, he gathers information doing questions to acknowledge friends to gain more reliable advice and the human ears can get easily downside prevails than positive aspects.

4.4.2 Bandwidth Modeling

The methodology used in this work is an adaptation of the methodology used in the following document:

"Multimedia Traffic Engineering - The Bursty Data Model"

John T. Chapman, January 8, 2002, Presented at SCTE Emerging Technologies 2002

For the perfect sizing of an access network and avoid all the flaws of service is important to determine the number of subscribers to be supported by the CMTS on the Head-End. This calculation is based on the network applications and ties of the service with the bandwidth used by a single user. The capacity of a CMTS depends on the available bandwidth and the bandwidth required by the user, as presents the following formula:

$$\frac{CMTS\ Bandwidth\ Available}{CM\ Bandwidth\ Required} = Number\ of\ CMs\ Supported; \qquad (21)$$

In the following calculations and conclusions, the limitations associated with the budgeting of power equipment is despised and It does not take into account any limitations Introduced by network equipment such as the CM, CMTS, or the WAN connectivity [45].

4.4.2.1 Modeling Data Traffic

The creation of a model allows the measure of results and data combinations enabling networks analysis and forecasting future situations.

Every user has a device in his house called CM to communicate with the CMTS (chapter 3.3). The services included on HFC network that occupy the bandwidth are:

- Data – includes all internet traffic (downstream and upstream data), email and low speed audio and video streaming;
- Voice – cover by IP (VoIP) and circuit switched equipment, presents constant bite rate and known bandwidth sized;
- Video (Tv) – broadcast video, MPGE encoded, only required for downstream.

Multimedia Traffic Engineering is a series of technical and engineering data models, to provide voice and video over an IP network. On this dimensioning we use Bursty data model, which is a particular technique used for HFC network engineering for data and it will be explained on the next chapter [45].

4.4.2.2 Bursty Data Model

The Bursty data model uses the criteria of measurement the interval allocated, the number of subscribers attending and their bandwidth requirements during that interval. To perform this description a measurement is carried out for three types of scenarios: average, peak and max scenario. The following figure 48 graphically illustrates the different types of scenarios:

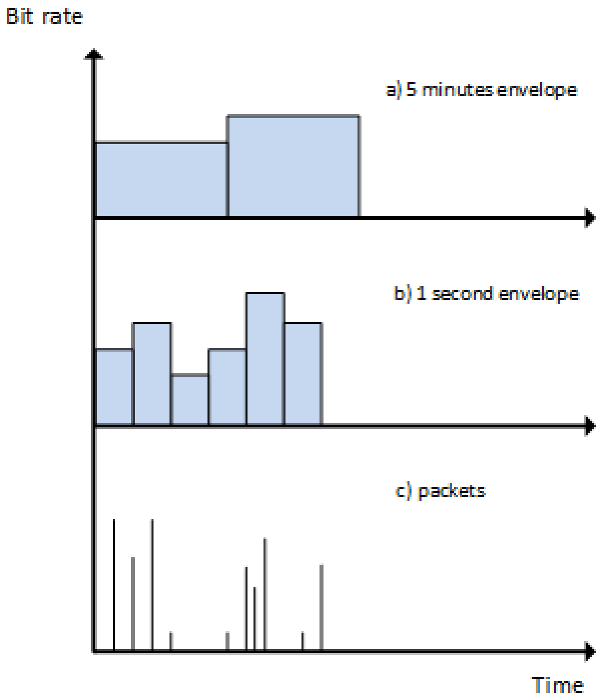


Figure 48 – Graphic representation (bit rate "vs" time) of different scenarios: a)Average; b)Peak; c)Max

Describing the differences between the examples presented, the average scenario shows the user access to the internet in a long time interval, being typical value of 5 minutes. In the peak scenario it is shown that an access by the subscriber lasts a shorter time in a loaded network. This scenario is usually chosen for better measures of user experience, lasting normally 1 second.

The max scenario is the rate seen by the user when the network is not loaded. This scenario represents the value that the CTMS uses to shape the traffic rate to the CM. Rate shaping is a DOCSIS feature in which the CMTS regulates the bytes within a DOCSIS service flow with a token bucket algorithm which regulates the peak and average value. When the flow of bytes exceeds the bounds of this equation, the CMTS introduces latency to the packet flow instead of dropping the packet. This latency causes protocols such as TCP to slow down. Thus, the CMTS is able to "shape" the TCP flow without actually causing any data loss 66 [45].

The average and peak scenarios are the two main scenarios, while the max scenario is more for completeness and to predict performance when rate shaping. The measurement interval for the max scenario is usually in the order of the milliseconds and is equal to the burst time of the token buck rate shaping algorithm. The bit rates for the peak and average are observed, but not enforced like the max scenario.

For the case study these 3 scenarios are used for the 2 types of communication between the CMTS and CM: upstream and the downstream. After measurement and analysis of the results the worst case scenario will define the operating limit sets for the CMTS, because it will be the maximum capacity that the network can support. Another important consideration in measuring systems of Bursty data traffic is to over subscribe the network aggressively enough to run at high bandwidth efficiency, to secure the operation of the network for every kind of performance [46].

Assuming that at a certain time 25% of the network users access the internet, the session density is 25% on average measurement interval and the session density parameters are the inverse of over subscription, so the over subscription is 4 (=1/25%). If the peak scenario had a session density of 20%, then the network would be oversubscribed by 20 (=1/(25%*20%)) during a 1 second measurement interval.

To determine the bit rate and packet size of the data profile for each scenario, is taken into account the values of the DOCSIS 3.0 protocol in ITU-T Recommendation J.222 (chapter 3.2) the calculations of bandwidth per physical layer for the two directions of traffic (upstream and downstream) are present in Appendix A. Using 256 QAM, approximately 40 Mbps of downstream payload bandwidth is available in a single 6 MHz RF channel[60]. With the values of bit rate and percentage of admission we reach the following values: upstream: 5,12 Mbps and 80% for data, downstream 37,78 Mbps and 90% for data [45][46][47]. The tables 15 and 16 show the values which characterize the user data profile:

UpStream	**User Profile**		
	Bit Rate kbps	Packet Size bytes	Packet Rate pps
Average	24	64	47
Peak	100	1518	8
Max	384	1518	32

Table 15 – User Data Profile values for Upstream

DownStream	User Profile		
	Bit Rate kbps	Packet Size bytes	Packet Rate pps
Average	80	400	25
Peak	256	1518	21
Max	2000	1518	165

Table 16 – User Data Profile values for Downstream

The value of Packet Rate (packet per second) is calculated through the following equation:

$$Packet\ Rate\ (User)(pps) = \frac{BitRate\ (kbps) \times 1000}{Packet\ Size\ (bytes) \times 8}\ ; \qquad (22)$$

Previously we spoke about session density, to know the how many users are using the network at a certain interval of time, so the following table displays how much bandwidth a single user used for the three scenarios, as shown in table 17:

Session Density (SD)	
Relative %	Direct %
25% of users	25%
20% of avg	5%
20% of peak	1%

Table 17 – Percentage of subscribers accessing the Internet

If the measurement interval for the average scenario was 60 minutes instead of 5 minutes, then it is obvious that many more users would have sent data, and thus the percentage would be higher. If the measurement interval was 12 hours, then the percentage could easily be 80%.

Continuing the calculations of the Bursty traffic model, using the values obtained from the user profile data along for all cases (max, peak and average) with the payload and admission (upstream and downstream) for DOCSIS 3.0 it is possible to determine the maximum capacity number of users. The next formulas and the tables 18 and 19 shows the calculations performed and the values obtained [47]:

$$Packet\ Rate\ (DS/US)\ (pps) = \frac{Payload\ (mbps) \times 1000000 \times Admission\ level\ (\%)}{Packet\ Size\ (bytes) \times 8}\ ; \quad (23)$$

$$Sessions\ (DS/US) = \frac{Packet\ Rate\ (DS/US)(pps)}{Packet\ Rate\ (User)(pps)}\ ; \quad (24)$$

$$Users\ (DS/US) = \frac{Sessions\ (DS/US)}{Session\ Density\ (\%)}\ ; \quad (25)$$

UpStream	User Profile			Upstream		Session Density (SD)	Users per US
	Bit Rate kbps	Pkt Size bytes	Pkt Rate pps	Pkt Rate pps	Sessions	Direct %	
Average	**24**	**64**	47	4848	103	25%	414
Peak	**100**	**1518**	8	300	36	5%	729
Max	**384**	**1518**	32	300	9	1,0%	950

US Bit Rate	**5,12**	Mbps
US Admission	**80%**	for Data

Max Users per Upstream: 414

Table 18 – Max users per Upstream Calculations

DownStream	User Profile			Downstream		Session Density (SD)	Users per DS
	Bit Rate kbps	Pkt Size bytes	Pkt Rate pps	Pkt Rate pps	Sessions	Direct %	
Average	**80**	**400**	25	10341	414	25%	1655
Peak	**256**	**1518**	21	2780	132	5%	2637
Max	**2000**	**1518**	165	2780	17	1,0%	1688

DS Bit Rate	**37,78**	Mbps
DS Admission	**90%**	for Data

Max Users per Downstream: 1655

Table 19 – Max users per Downstream Calculations

For each scenario was obtained minimum number of users for downstream and upstream. The smaller for each direction from the 3 scenarios is used as the limit for the maximum number of users for CMTS capacity.

$$Users\ per\ Domain\ (DS/US) = Users\ (DS/US) \times Domain\ Ratio; \quad (26)$$

As previously referred, the minimum amount of users per domain between the two directions of traffic data flow will be chosen, being then possible to deduce the number of subscriber limiting the system. This user limit is then divided by users per households passed (HHP) to get the number of subscribers that can be supported [45]. That number is then divided by the market penetration of data (MP of data) to determine the number of HHP that the DOCSIS domain can support. The next formulas and table 20 shows the system limit:

$$Users\ per\ Direction\ (DS/US) = \frac{Users\ (limit)}{Users\ per\ HHP \times Domain\ Ratio}; \quad (27)$$

$$Max\ HHP\ (DS/US) = \frac{Users\ per\ Direction\ (DS/US)}{Market\ Penetration\ of\ Data\ (\%)}; \quad (28)$$

Direction	Domain Ratio	Users Allowed	Users per Domain		Users per Direction	Max HHP per Direction
			max	limit		
Upstream	**6**	414	2482	1655	184	1838
Downstream	**1**	1655	1655		1103	11030

Users per HHP	**1,5**
MP of data	**10%**

Table 20 – Max users per Direction Calculations

This system is upstream limited, by 1838 HHP. Figure 49 shows the evolution of the number of HHP with the growth in the value of market penetration:

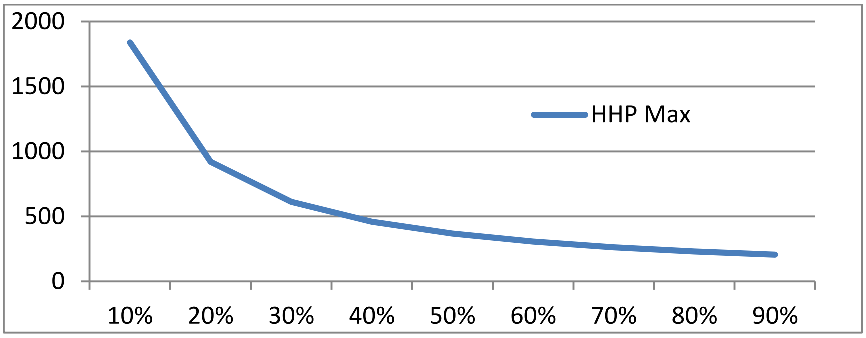


Figure 49 – Graphic representation of HHP max value for market penetration growth

The media profile refers to the DOCSIS upstream as downstream and relatively constant. If the user data profile and session densities are known, then the number of users a network will support can be determined. If we reversed the process of calculation, it is possible through the session density and the number of users covered by the CMTS to determine the bandwidth available to each subscriber.

The next diagram on figure 50 illustrates high level view of the parameters of the Bursty Data Model:

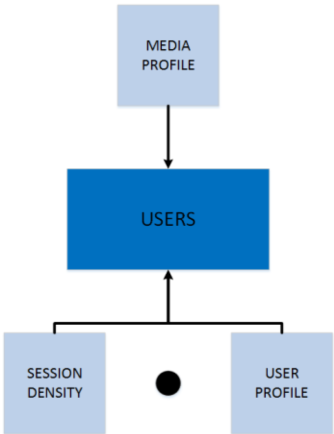


Figure 50 – Bursty Data Model

To conclude, the engineering process for dimensioning a network - Bursty Data Model provides a simple and useful method for establishing a profile for a data user. This method can estimate the coverage limit of HHP for bandwidth and payload of a CMTS, or calculate the bandwidth available to each user knowing the number of CMs that are covered and the session density.

5. Technical and Economic Analysis of an HFC network: case studies

To complete the study of HFC network dimensioning, a techno-economic analysis is performed. For the implementation of this network, it is necessary to define some important assumptions:

- The existence of base the infrastructure necessary for the implementation of coax cables and fiber, without spending costs on trenching and poles;
- The investment will be phased, depending on the rate of penetration and area covered. This investment serves to reduce the cost of capital raised in the initial year;
- The equipment used in the Head-End is destined only to the HFC network;
- The limitations associated with the budgeting of power equipment is despised and it does not take into account any limitations introduced by network equipment such as the CM, CMTS, or the WAN connectivity.

It is also important to note, that the analysis of this implementation corresponds to a long-medium project term. The calculations extend to 15 years after the starting date of implementation. The database and the amount of equipment used are based on its function and granularity with the ability to cover more than one user – (this rule applies to both the Head-End and the Feeder Network).

5.1 Budgeting Tool

To perform this analysis was a tool was used, to realize all the calculations: the Microsoft Excel [40]. The next figure provides the structure employed, well as the parameters and methods used in this program:

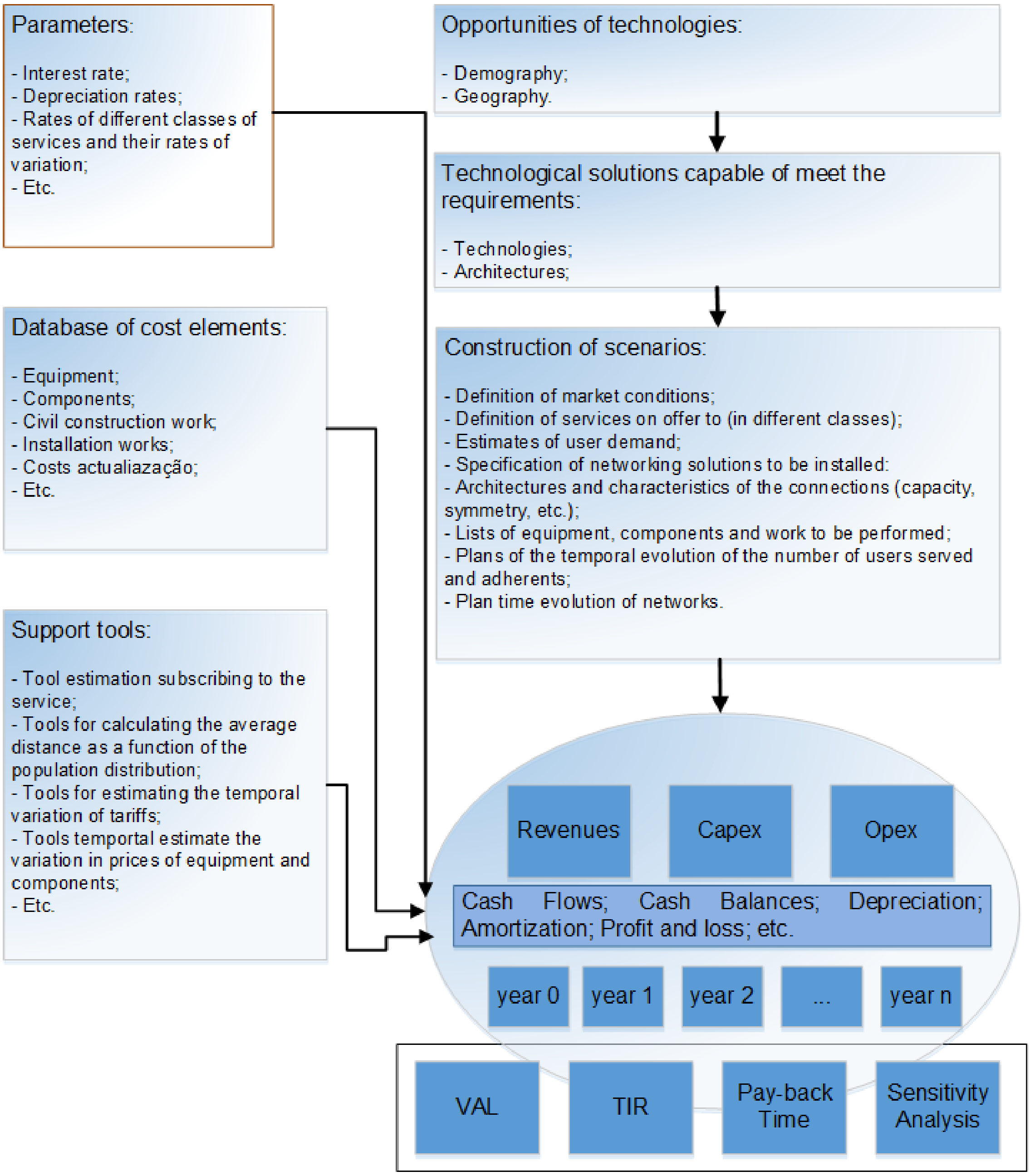


Figure 51 – Structure of analysis technical-economic tool [52]

5.2 Market

The market scenario investigation is organized in two phases:

- The qualitative, which studies the need for the deployment of access networks to an emerging country that had a fast economic growth in the past few years and has an unique chance to invest and models already in use in other locations;
- The quantitative, which analyzes the economic and financial viability by installation of new telecommunications models.

Good examples of this kind of country are Angola, Mozambique and Brazil, Angola's Annual average GDP (Gross Domestic Product) growth was 11.1% [48] and in Brazil was worth 2476.65 billion US dollars in 2011, represent 3.99% of the world economy [49]. Brazil is the seventh largest economy in the world and the largest in Latin America. In recent years, the country has been one of the fastest-growing economies in the world primarily due to its export potential [49]. Note that the GDP measures the national income and outcome for a given country's economy. But a country like Brazil already has major implementation studies of new access networks, with competition from companies like, OI (PT partnership), Vivo (Telefonica partnership), and the group Embratel, Net and Claro (America Móvil property). Angola and Mozambique have also excellent relationships with Portugal Telecommunications companies and an excellent potential due to its unexplored market.

Speaking about Angola, the capital and largest city is Luanda, located on Angola's coast with the Atlantic Ocean. Angola presents itself as one of the mains emergent markets in the world, with a fast growing economy. Telecommunications are not an exception and the operators have tried to follow in an active way this growth. The population of Luanda has grown dramatically in recent years, due in large part to war-time migration to the city, which is safe compared to the rest of the country. It has a metropolitan population of over 5 million people [50].

Economic growth is expected to reach 8.2% in 2013 and 7.8% in 2014, driven by the expansion of the oil and gas sector and a public expenditure program designed to encourage economic diversification [51]. The Government has implemented ambitious reforms to improve governance, but the business environment remains difficult due to lack of infrastructures and institutions. The next figure 52 shows the population growth in Angola and Luanda based on the data from United Nations, Economic and Social development [50]:

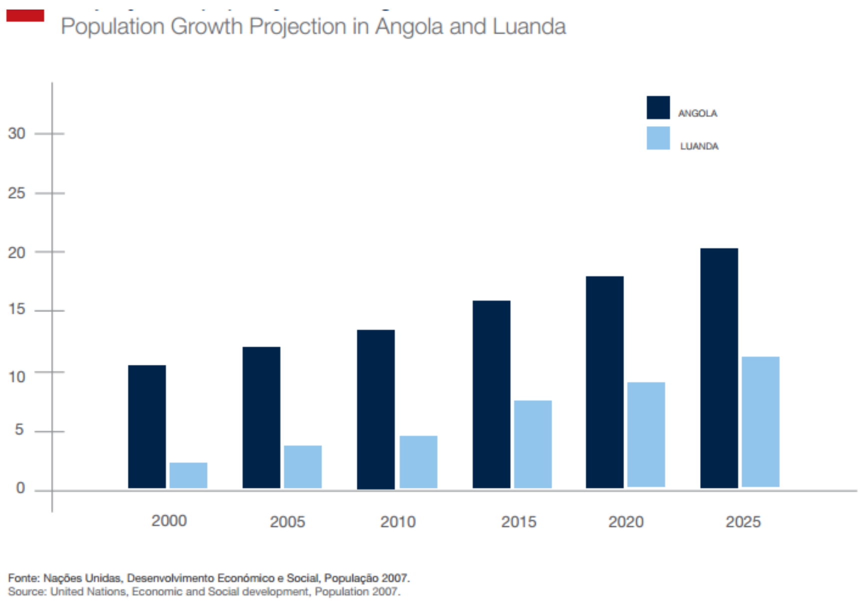


Figure 52 - Graphic representation of Population Growth Projection in Angola and Luanda (Million habitants) [50]

5.3 Input Values

To analyze the market available we need to set the rate of penetration of our product. For the evolution of penetration three perspectives are considered: optimistic, pessimistic and median. To get this rate of penetration we use this formula [52]:

$$P(t) = P_i + \frac{(P_i - P_f)}{1 + \alpha . e^{\beta . t}} , \quad (29)$$

where:

Pi = initial rate of penetration;

Pf = final rate of penetration;

a = control parameter for start market;

b = speed control parameter for start market;

t = year for which you want to know the rate of penetration.

With formula (29) it is possible to obtain a graphic of the logistic curve "S", which allows the control of the number of people adhering to the network and the rate of penetration of the service, along a certain time.

5.3.1 Cost Elements Network

The information needed for the elements of cost required for the implementation of a HFC network is present in two groups: the identification of components, characteristics and attributes; reference cost and its temporal evolution.

On chapter 3.4 are explained the organization of the elements, while their respective costs are presented on Appendix B. The implementation costs and labor services are described on chapter 4.1.2.

5.3.2 Phased Implementation Network

Each element can accommodate a certain capacity for users considering the implementation costs over discrete time proportional to a unit time (year). Whenever there is a new installation, is added an intervention with a price, not depending on their size. When the number of users exceed the capacity of the existing equipment (phasing in unexpected initial), requires an intervention with not expected costs. To decrease the number of interventions is created, when implementing, a margin of safety equipment to cover extraordinary cases.

The usual cost of an intervention is 20.000€. The following function represents an approximation of a function of continues capacity through a discrete function [53]:

where:

t – time (year);

C – Capex;

Δ – time interval for installation (15% market);

µ - installation fee (20% market).

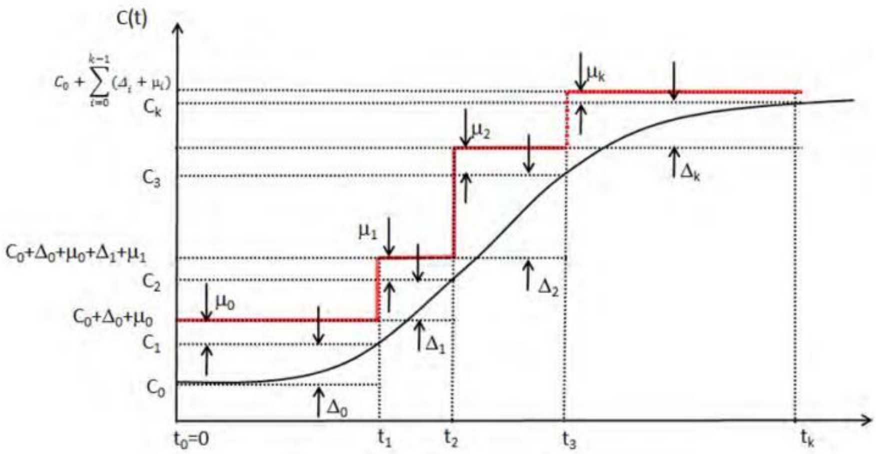


Figure 53 - Approximation of a continuous function capability through a discrete function [53]

5.4 Output values

5.4.1 Capex

Capital Expenditure (Capex) is an expenditure associated with the implementation or extension of fixed assets (such as infrastructures), subject to depreciation over the economic life of an investment's project [54]. To determine the value of Capex are predicted and calculated the costs associated with the implementation of a network, acquisition of equipment, such as software and hardware for the services required and the labor required.

In the case study presented, capital costs are the sum of the necessary equipment, manpower and infrastructure necessary to implement the following. It will also be presented, the annual investment accumulated and the aggregate value depreciated and the depreciation of equipment already purchased devalues at a rate of 10% per year. For any class of equipment the following formulas explain the associated investment costs:

$$Invest\ accum_{year\ M} = Invest_{year\ M} - Invest_{year\ M-1}; \quad (30);$$

$$Invest\ accum\ (depreciate)_{year\ M} = Invest_{year\ M} \times (1 - depreciate\ rate) - Invest_{year\ M-1}; \quad (31);$$

The initial investment is called "time 0" before any economic activity, but the associated costs are present in the first year, where there is already some user's adherence.

To present organization, the investments are divided into 3 groups of HFC elements network:

- Head-End network;
- Feeder / Distribution network;
- Drop (User House) network.

Using the data from the equipment and installation, as their respective price and user granularity present in Appendix B, the need for equipment by number of customers is present at the next table 21:

Item 1	1	per	1	user	**Drop (User Network)**	Router, STB, CM, Telp IP
Item 2	1	per	8	user	**Feeder / Distribution network;**	Coax Cable / TAP
Item 3	1	per	16	user		Pwr Splitter / RF Amplifier
Item 4	1	per	98	user		Optical Fiber / Joint / Optical Node / ROM
Item 5	1	per	288	user		Cabinet Joint
Item 6	1	per	24	user	**Head End Network**	EDGE QAM
Item 7	1	per	42	user		Rack / SubRack
Item 8	1	per	64	user		CMTS
Item 9	1	per	128	user		WDM

Table 21 - Number of Equipment by Subscriber Number

To finish the description of capital costs, lack the length of optical fiber and coaxial cable needed to cover the entire area along the implementation time. The price of each wiring equipment depends on its length, while the length depends on the geographic and demographic distribution of the population. Using information from chapter 4.1.2 and Appendix C is possible to know the wire lengths values.

5.4.2 Opex

Operational Costs (Opex) are the expenses associated with administering a business on a day to day basis. The outgoing doesn’t aim to increase the company's assets and shows no residual value, so it is not subject to any depreciation also.

To keep active and functional the services, part of the cost is associated with the number of customers and the rest, expected long duration of this kind of project, consist mainly of a percentage of the cumulative Capex. The next formula represents Opex expenses [55]:

$$Opex = 10\%\ Cumulative\ Capex + User\ Equipment\ (marge) \times User\ Numbers; \qquad (32)$$

The value of the user equipment is around 120,00€, the subscriber buys the IP telephone and leases the terminal STB (5.00 € per month), leaving the Modem DOCSIS (CM) and Router. In general, the Opex can be defined as all cost elements in an analysis of cash flow aside from the ones present on the Capex.

5.4.3 Revenues

The revenue is the income that a company receives from its normal business activities, on telecommunications business and this money come from the sale of the services to customers. The amount of return depends heavily on the tariffs imposed. For the calculation of the income, it was considered the sale of our main product (triple play package) and taken into account a price erosion of 3% [55]. Formula 33 and table 22 represents an example of the calculation of the revenues evolution, with the product annual cost equal to 420,00 €, 450,00 €, 500,00 €:

$$Cost\ per\ year_M = Cost_{year\ M-1} - (Cost_{year\ M-1} \times \%erosion); \qquad (33)$$

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
500 €	485 €	470 €	456 €	443 €	429 €	416 €	404 €	392 €	380 €	369 €	358 €	347 €	337 €	326 €
450 €	437 €	423 €	411 €	398 €	386 €	375 €	364 €	353 €	342 €	332 €	322 €	312 €	303 €	294 €
420 €	407 €	395 €	383 €	372 €	361 €	350 €	339 €	329 €	319 €	310 €	300 €	291 €	283 €	274 €

Table 22 – Service cost per year all over the years of the network (●Optimistic; ●Median; ●Pessimistic)

After obtaining the cost per year over the years of the network, the final income value is calculated simply by multiplying the Cost/year by the number of users that adhere to the service, as is showed on formula 34. For every different scenario the amount of revenue depends solely on the number of network subscribers.

$$Revenues = N^{o}\ Users \times Cost\ per\ year_M; \qquad (34)$$

5.4.4 Cash-Flow

The cash flow represents the cash flows, so comprises receipts (cash inflows) and payments (cash outflows) over a defined time period. In the calculation of the cash flow are also considered other parameters, such as profit before tax and amortization. However, shall not be taken into account in this financial year, since taxes on profits were ignored. Knowing the value of capital and operating costs and revenues, it is possible to calculate the annual cash flow for each year M, as shown in the next formula 35:

$$Annual\ Cash\ Flow_M = -Capex_M - Opex_M + Revenues_M \ ; \tag{35}$$

Based on cash flow annual, the value balance at the end of each year M is calculated through the formula 36:

$$Balance_M = Balance_{M-1} + Annual\ Cash\ Flow_M \ ; \tag{36}$$

The evaluation criteria of investment that an operator should take into account when deciding on the feasibility of an investment project are:

- NPV (Net Present Value): described as the “difference amount” between the sums of discounted: cash inflows and cash outflows. It compares the present value of money today to the present value of money in the future, taking inflation and returns into account [56]. Also is the indicator of how much value an investment or project adds to the company. (If > 0 the project may be accepted, else the project should be rejected);

$$NPV = \frac{R_n}{(1+iR)^n} \ ; \tag{37}$$

- IRR (Internal Return of Rate): is a return fee used in the capital budget for measuring and comparing the return on investments [56];

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} = 0 \ ; \tag{38}$$

- Pay-back period: is the time at which the value generated by the business exceeds the sum of all investment to date (Cash Flow = 0 and never back to negative values);

  To better understand the formulas above the constants must be defined:
  n is the year;
  C is the Cash Flow;
  r is the IRR

iR is the Interest Rate (5% - The rate used to discount future cash flows to the present value)

5.5 Scenarios Study

Now it is necessary to choose models to analyze different scenarios (urban, rural and sub urban) in a country like Angola, where the population distribution isn't easy to interpret – (the capital has a high population density, while peripheral zones will decrease this density and finally the interior of the country reveals very poor and in a state of underdevelopment, with many dwellings without water and electricity). Using the data in the market analysis and dimensioning methods used in chapter 4.1, a techno economic analysis of the implementation of an HFC network for each scenario was conducted.

The residential market in Luanda has been very active only in recent years. Since 2002 the market has grown strongly but has been unable to meet the requirements of such a fast growing urban population, and has become very dynamic in terms of price performance, with costs growing rapidly. The main residential districts in Luanda are: Downtown Luanda, Alvalade, Cruzeiro, Miramar, Talatona and Bairro Azul [57]. The next figure shows the location of the main residential districts in Luanda (urban scenario):

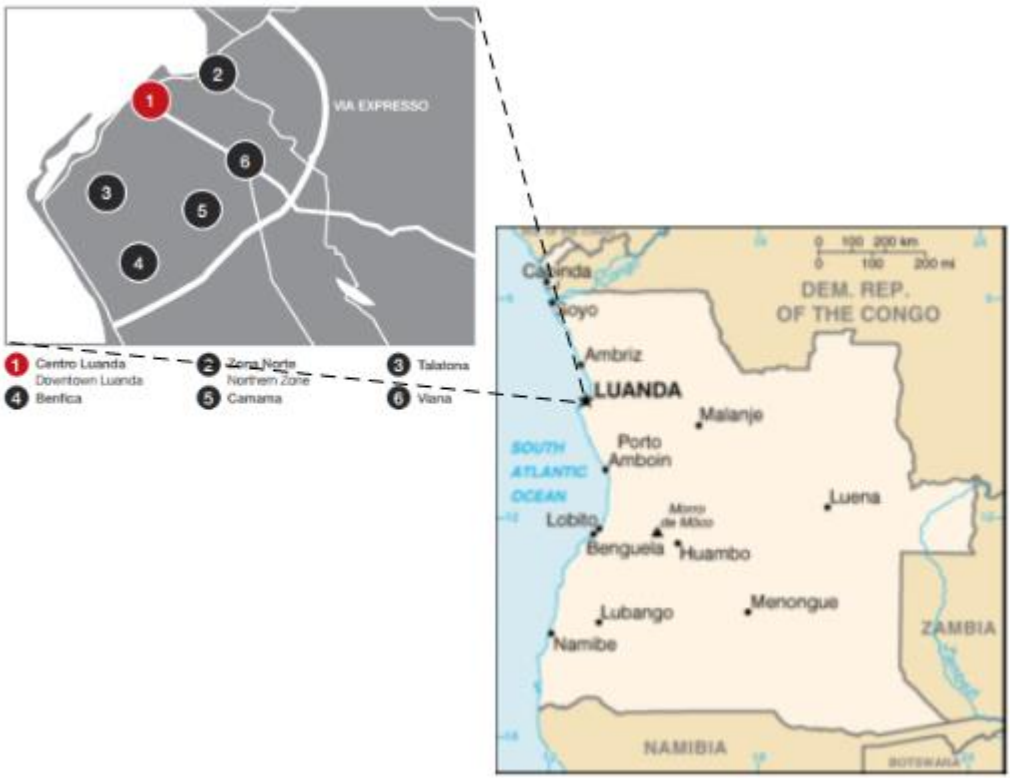


Figure 54 – Residential Districts in Luanda [58]

Angola recorded a large deficit of recent demographic data. Since its independence in 1975, the country never held a census of the population, while the next one is scheduled for 2014 [43]. The civil war situation in which the country is plunged from 1975 till 2002 didn't allow this operation statistics. So we assume a number of 4 habitants per house, common value in emerging countries.

5.5.1 Urban Scenario

With this information, it is possible to assume that a place such as Downtown Luanda (urban scenario) has a number of a hundred thousand of houses to offer telecommunications services, in an extension of 20 km^2. The following picture represents Downtown Luanda using the service Google Maps [59]:

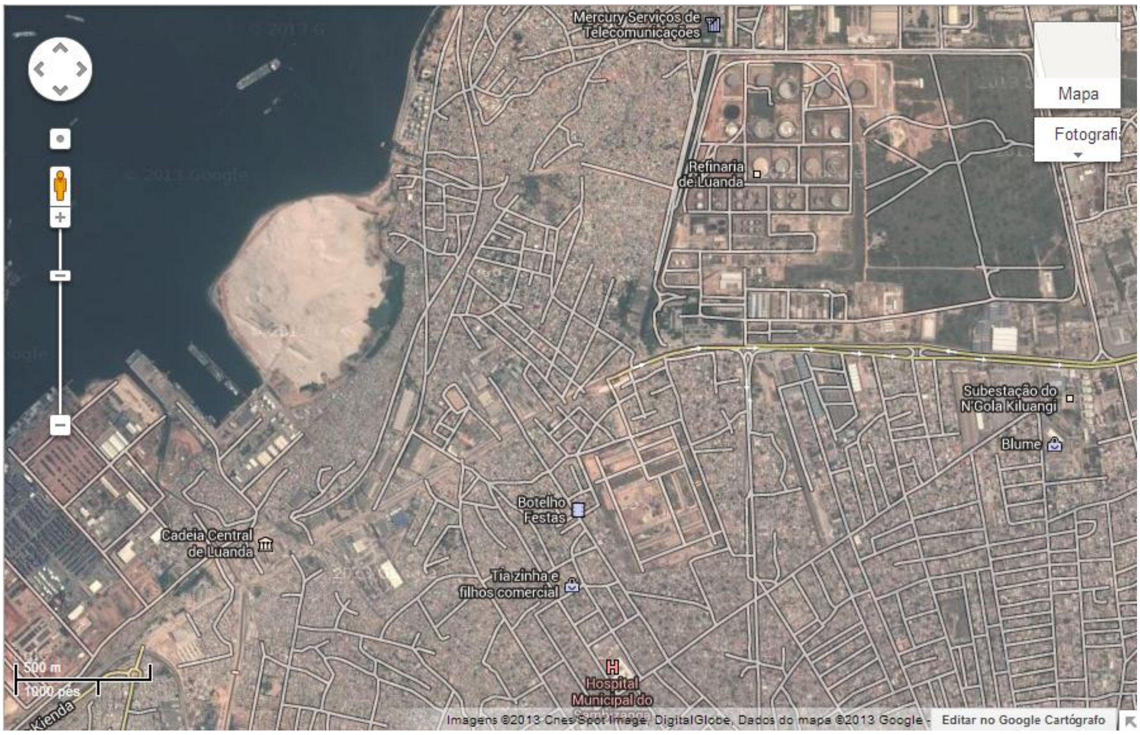


Figure 55 – Downtown Luanda (urban scenario) Google Maps data base

5.5.1.1 Market Penetration

In terms of market penetration in the population of Downtown Luanda, table 23 and figure 56 - represent the variable values and the number of clients adherent along the years:

URBAN											
Optimist				**Median**				**Pessimist**			
P_Start	P_Final	α	β	P_Start	P_Final	α	β	P_Start	P_Final	α	β
20%	80%	1000,00	-1,50	15%	70%	2500,00	-1,50	10%	60%	3000,00	-1,50

Table 23 – Variable values for penetration evolution in Urban scenario

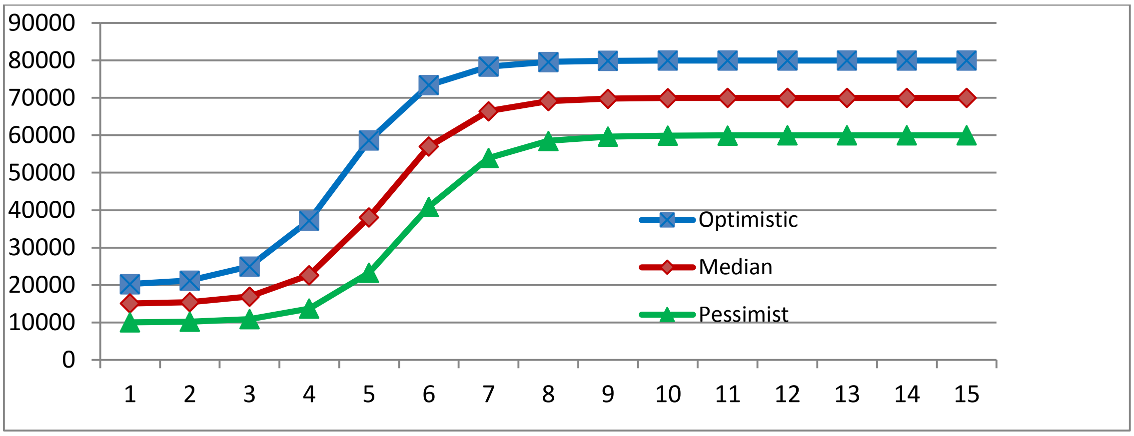


Figure 56 – Graphic perspective of number of clients along the years for Urban scenario

5.5.1.2 Capex

Using the values presented on chapter 4 to describe the population distribution on the urban scenario (uniform) and the length of wiring required, we now show the capital costs for the implementation of the HFC network over 10 years (the values of Capex in last 5 years of implementation are very low compared with previous investments.) on the table 24 and its illustration on figure 57:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
33.716.243 €	1.560.985 €	5.713.423 €	16.542.502 €	25.513.733 €	15.742.623 €	4.771.708 €	1.088.596 €	217.642 €	45.827 €
21.219.635 €	501.559 €	1.916.147 €	6.694.156 €	15.995.918 €	17.589.758 €	7.928.396 €	2.070.989 €	452.469 €	79.024 €
14.123.633 €	6.645.392 €	2.674.730 €	8.163.053 €	15.200.751 €	15.320.896 €	8.244.821 €	2.495.821 €	578.161 €	123.616 €

Table 24 – Capex cost for Urban Scenario (•Optimistic; •Median; •Pessimistic)

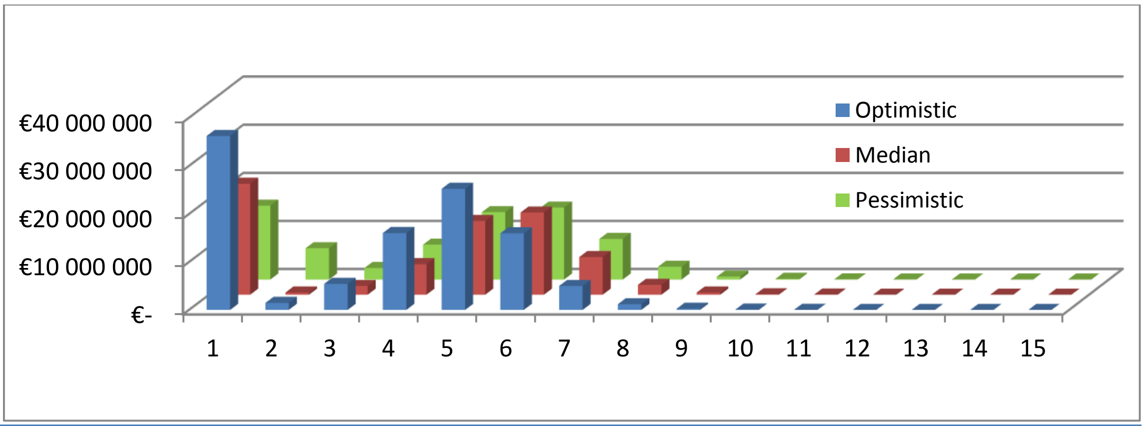


Figure 57 – Graphic representation of Capex to Urban Scenario

5.5.1.3 Opex

When it comes to operating costs, this indicator is dependent on the phased investment accumulated and the number of customers, as shown in the following table 25 and figure 58:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
5.809.103 €	5.755.957 €	6.536.546 €	9.567.471 €	14.637.496 €	17.597.512 €	18.000.312 €	17.540.441 €	16.922.827 €	16.322.909 €	15.773.273 €	15.276.362 €	14.828.818 €	14.425.957 €	14.063.366 €
3.935.921 €	3.822.090 €	4.026.638 €	5.313.209 €	8.859. 640 €	12.927.340 €	14.540.248 €	14.587.461 €	14.213.519 €	13.778.087 €	13.366.888 €	12.991.232 €	12.652.324 €	12.347.139 €	12.072.436 €
2.618.811 €	3.164.474 €	3.336.905 €	4.362.484 €	6.994. 640 €	10.678.898 €	12.876.847 €	13.248.355 €	12.965.456 €	12.554.393 €	12.148.857 €	11.776.123 €	11.438.907 €	11.135.105 €	10.861.614 €

Table 25 - Opex cost for Urban Scenario (•Optimistic; •Median; •Pessimistic)

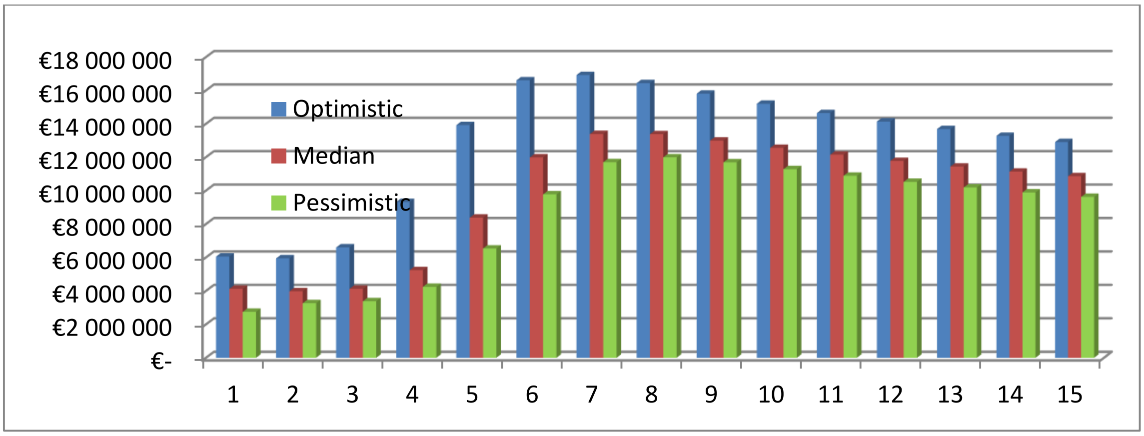


Figure 58 – Graphic representation of Opex to Urban scenario

5.5.1.4 Revenues

The proceeds of the investment come from the payment of an amount, either monthly or yearly, by the customer for a service benefit. In this situation there is only one service to chosen - (triple play, chapter 3.5) and has an annual cost of € 500,00. These annuities devalue over the study period, as explained in formula 33. The following table 26 and graph 59 show these values:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
11.171.775 €	11.405.325 €	13.341.448 €	20.140.126 €	31.684.082 €	38.875.460 €	40.372.701 €	39.805.188 €	38.753.985 €	37.622.487 €	36.500.557 €	35.407.000 €	34.345.106 €	33.314.821 €	32.315.391 €
7.558.158 €	7.526.260 €	8.119.545 €	10.966.538 €	18.715.024 €	27.768.998 €	31.575.273 €	31.922.057 €	31.262.731 €	30.390.362 €	29.492.876 €	28.611.171 €	27.753.503 €	26.921.042 €	26.113.442 €
5.026.866 €	4.966.430 €	5.203.695 €	6.607.615 €	11.479.800 €	20.225.173 €	26.129.833 €	27.556.932 €	27.270.943 €	26.573.257 €	25.802.297 €	25.033.915 €	24.284.129 €	23.555.872 €	22.849.253 €

Table 26 - Revenues for Urban Scenario (●Optimistic; ●Median; ●Pessimistic)

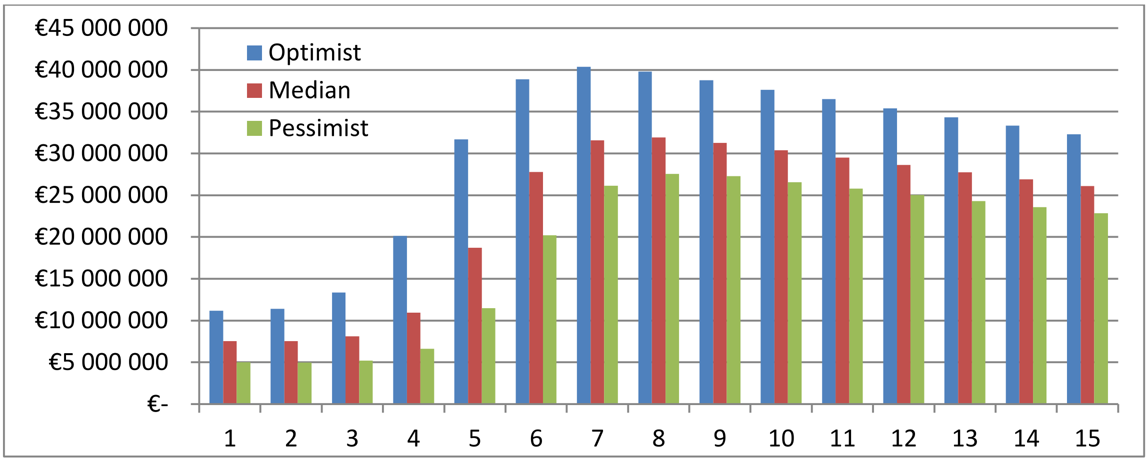


Figure 59 – Graphic representation of Revenues to Urban scenario

5.5.1.5 Results

The following figures show the calculations carried out for the results (using the Microsoft Excel [40] calculation formulas) of this scenario: Cash Flow, NPV, IRR and Pay-back period:

The table of results is present on Appendix D.1.

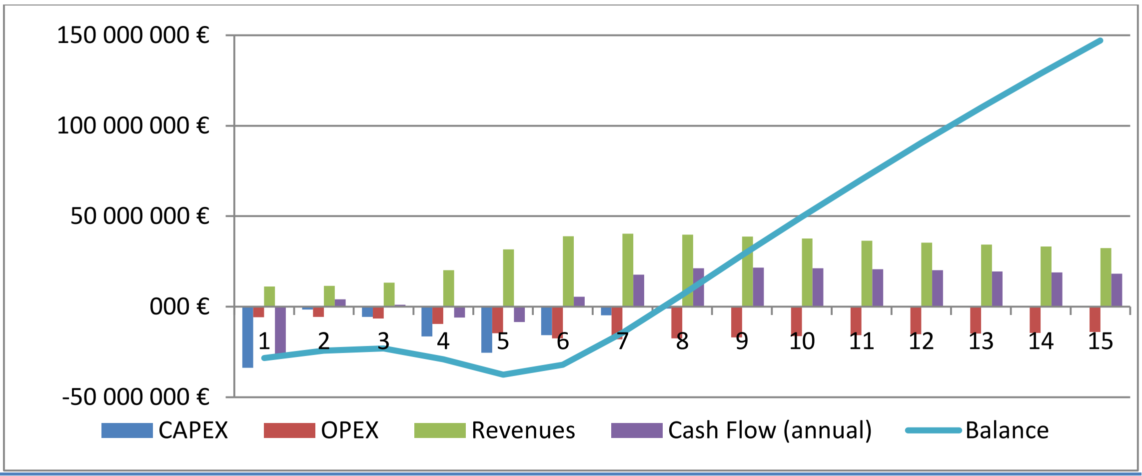


Figure 60 – Urban scenario Optimistic Results

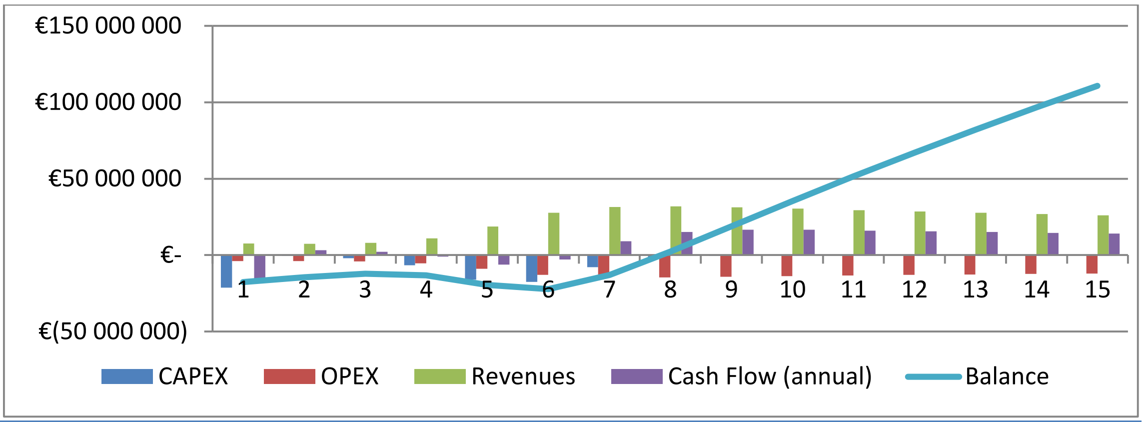


Figure 61 – Urban scenario Median Results

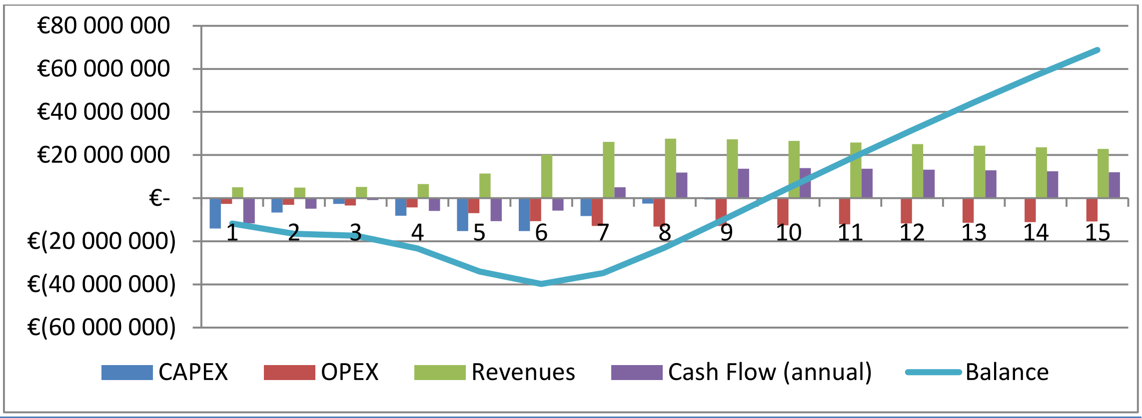


Figure 62 – Urban scenario Pessimistic Results

5.5.2 Rural Scenario

Continuing the selection of different scenarios, as a model for the rural scenario, a search was made from a little distance of Luanda, directed to the interior zone of the country, which is characterized by scattered and low population density areas. For an informed choice of this kind business, it is smart to choose an area where it is possible to invest for an implementation of access networks, because there are still many regions where poverty is a common and more important needs to increase those regions development.

The chosen area is Caxito (the distance to the center of Luanda is shown in the Figure 63, from Google Maps [59]), has 3000 houses and an area of 4 km^2. Figure 64 demonstrates Caxito demography and street morphology.

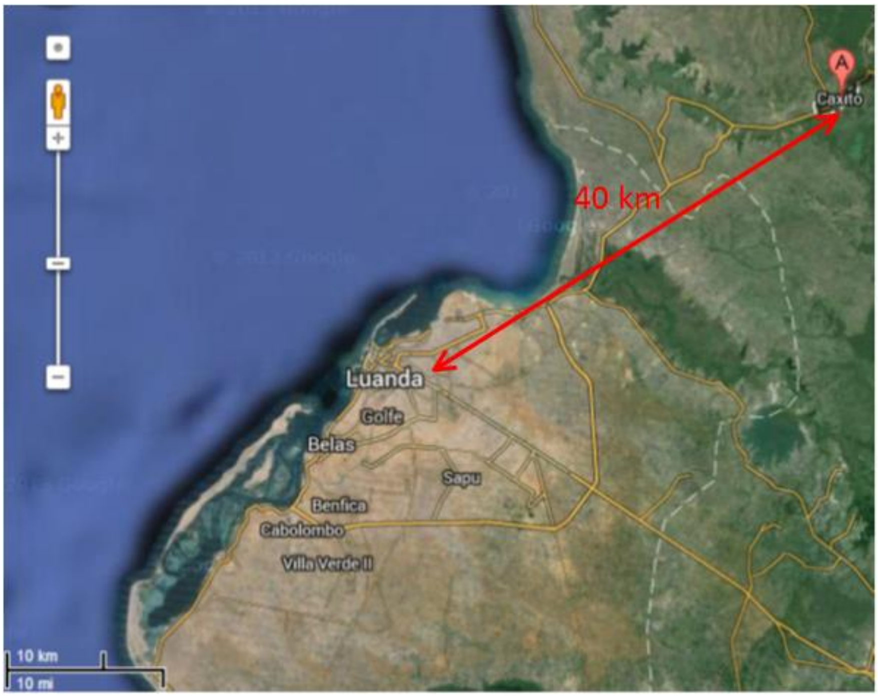


Figure 63 – Representation of Caxito distance from Luanda city

Figure 64 – Caxito (rural scenario) Google Maps data base

5.5.2.1 Market Penetration

For the rural scenario the market penetration is slower and has less population. Table 28 and figure 65 represent the number of clients along the years:

RURAL											
Optimist				Median				Pessimist			
P_Start	P_Final	α	β	P_Start	P_Final	α	β	P_Start	P_Final	α	β
15%	60%	1000,00	-1,50	10%	50%	2500,00	-1,50	5%	40%	5000,00	-1,50

Table 27 - Variable values for penetration evolution in Rural scenario

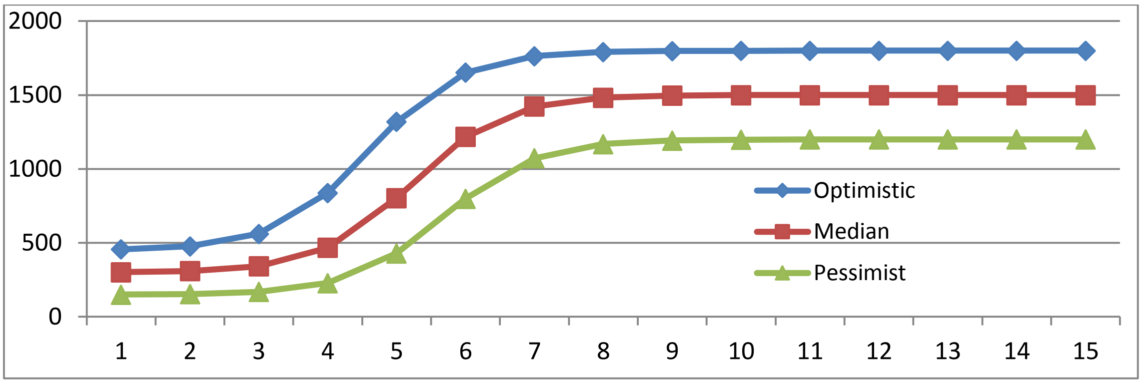


Figure 65 – Graphic perspective of number of clients along the years for Rural scenario

5.5.2.2 Capex

Again using the values presented on chapter 4.1 to describe the population distribution (gaussian) and the length of wiring, it is possible to determine the Capex of the HFC network implementation over 10 years (the values of Capex in last 5 years of implementation are very low compared with previous investments.) - table 29 and figure 66 represent the capital costs:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1.205.570 €	16.386 €	173.689 €	500.358 €	750.721 €	457.567 €	146.058 €	42.664 €	12.588 €	126 €
750.072 €	7.855 €	49.880 €	194.513 €	496.804 €	514.354 €	236.963 €	80.258 €	4.870 €	3.151 €
383.188 €	198.797 €	56.029 €	185.385 €	403.319 €	466.803 €	248.497 €	92.212 €	35.343 €	485 €

Table 28 – Capex cost for Rural Scenario (●Optimistic; ●Median; ●Pessimistic)

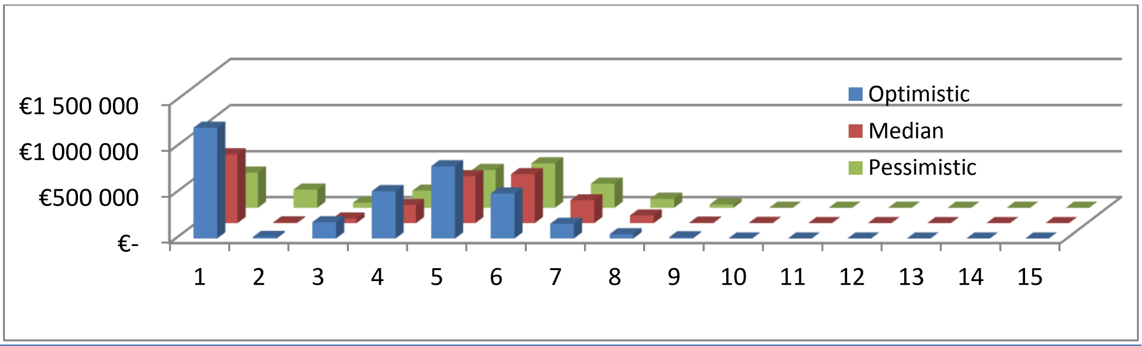


Figure 66 – Graphic representation of Capex to Rural Scenario

5.5.2.3 Opex

The operating costs values to the rural scenario are represented in the following table 30 and figure 67:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
175.28 0 €	167.33 0 €	183.87 3 €	255.45 0 €	372.77 4 €	436.97 9 €	441.16 2 €	425.83 0 €	406.77 5 €	387.86 0 €	370.71 0 €	355.24 7 €	341.32 4 €	328.79 2 €	317.51 3 €
111.26 5 €	105.44 0 €	107.45 6 €	135.26 6 €	217.44 7 €	306.39 4 €	338.73 3 €	337.05 4 €	323.30 5 €	309.62 2 €	296.74 0 €	285.08 4 €	274.57 9 €	265.12 2 €	256.61 0 €
56.432 €	72.871 €	74.761 €	95.025 €	152.65 1 €	233.66 9 €	277.57 6 €	283.40 8 €	275.52 3 €	262.99 9 €	251.24 0 €	240.54 7 €	230.89 9 €	222.21 1 €	214.39 0 €

Table 29 - Opex cost for Rural Scenario (●Optimistic; ●Median; ●Pessimistic)

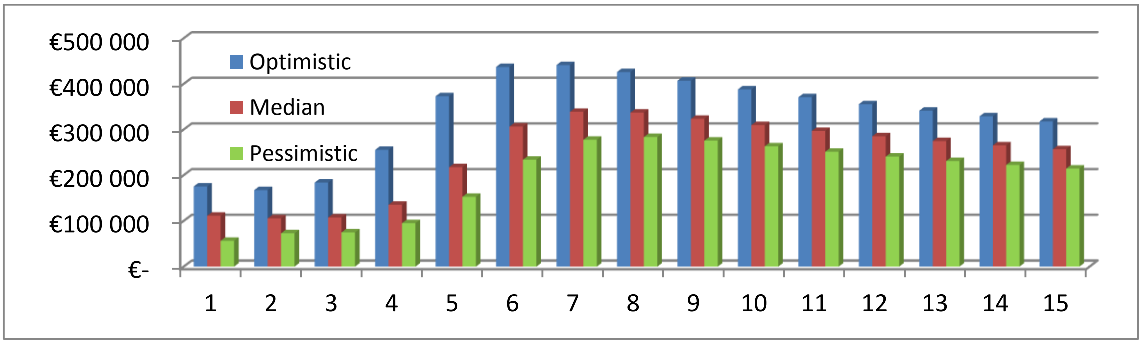


Figure 67 – Graphic representation of Opex to Rural scenario

5.5.2.4 Revenues

Regarding the revenues in this situation the service available has an annual cost of 420,00 €, triple play (section 3.5). These annuities devalue over the study period, as explained in formula 33. The following table 31 and graph 68 represent the income values:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
216.611 €	219.585 €	250.944 €	363.320 €	554.758 €	673.726 €	697.877 €	687.661 €	669.413 €	649.848 €	630.465 €	611.576 €	593.234 €	575.438 €	558.175 €
126.902 €	126.116 €	135.035 €	178.912 €	298.807 €	438.956 €	497.733 €	502.869 €	492.409 €	478.653 €	464.514 €	450.626 €	437.118 €	424.006 €	411.287 €
63.395 €	62.822 €	66.615 €	87.549 €	159.457 €	288.293 €	375.362 €	396.603 €	392.654 €	382.644 €	371.551 €	360.488 €	349.691 €	339.205 €	329.029 €

Table 30 - Revenues for Rural Scenario (●Optimistic; ●Median; ●Pessimistic)

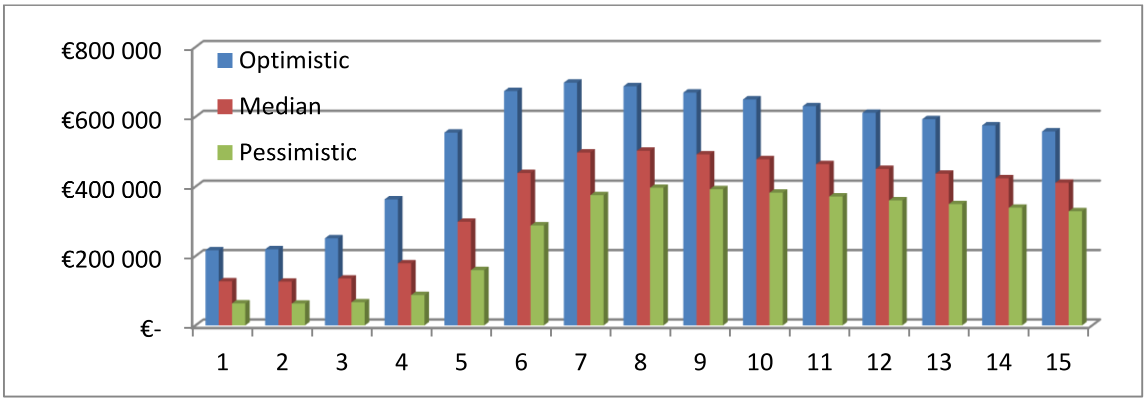


Figure 68 – Graphic representation of Revenues to Rural scenario

5.5.2.5 *Results*

The table of results is present on Appendix D.2. The results obtained are shown figures 69, 70 and 71:

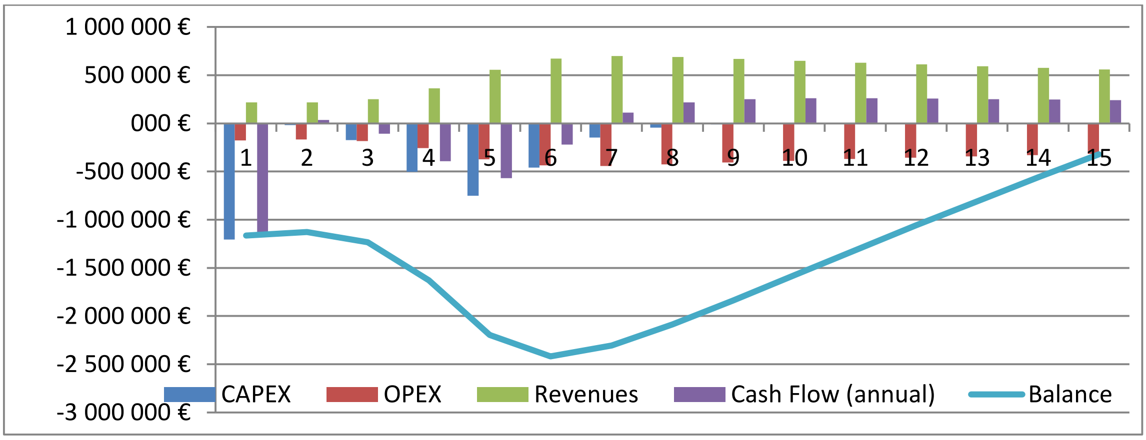


Figure 69 – Rural scenario Optimistic Results

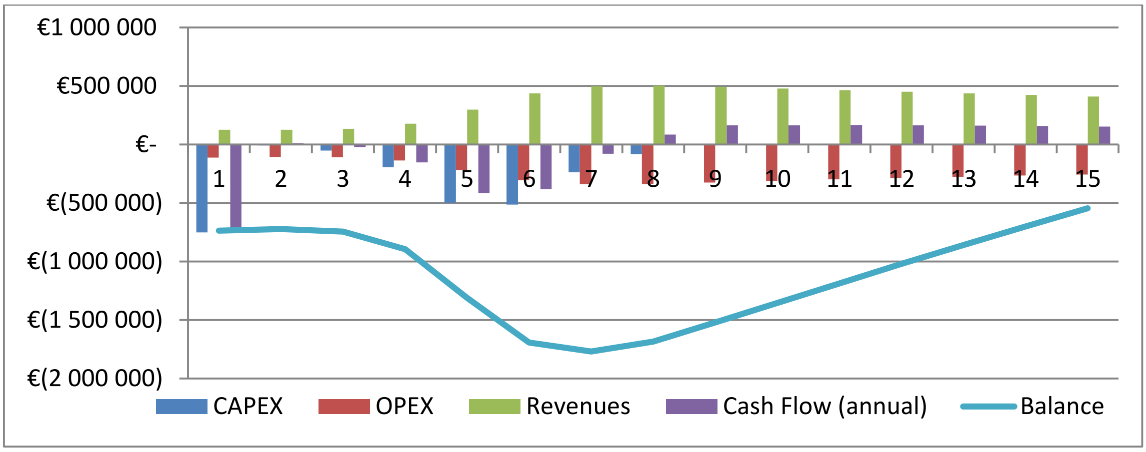


Figure 70 – Rural scenario Median Results

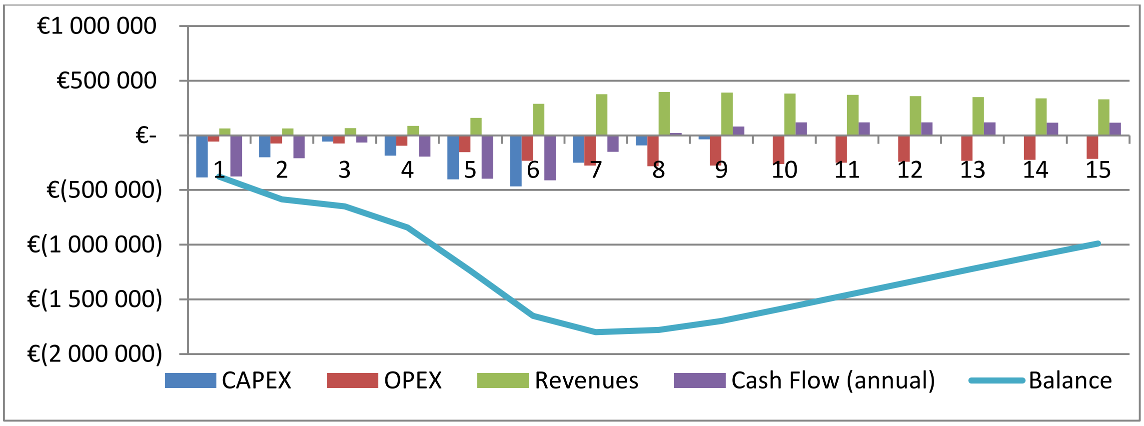


Figure 71 – Rural scenario Pessimistic Results

5.5.3 Suburban Scenario

Ultimately, to characterize the suburban model the metropolitan area of the capital Luanda was chosen, where the values of population density are relatively lower than those of the city Center.

As seen in Figure 54, one of the metropolitan areas of south Luanda is the region of Benfica in the province of Bengo, which presents an extension of 24 km^2 and thirty thousand houses. The following image 72 shows the region of Benfica using again the Google Maps service [59]:

Figure 72 – Benfica (suburban scenario) Google Maps data base

5.5.3.1 *Market Penetration*

About the market penetration and adherence of the population on the suburban scenario - table 33 and figure 33, represents the values expected along the years:

SUBURBAN											
Optimist				**Median**				**Pessimist**			
P_Start	P_Final	α	β	P_Start	P_Final	α	β	P_Start	P_Final	α	β
15%	75%	1000,00	-1,50	10%	70%	2500,00	-1,50	5%	65%	5000,00	-1,50

Table 31 - Variable values for market penetration evolution in Suburban scenario

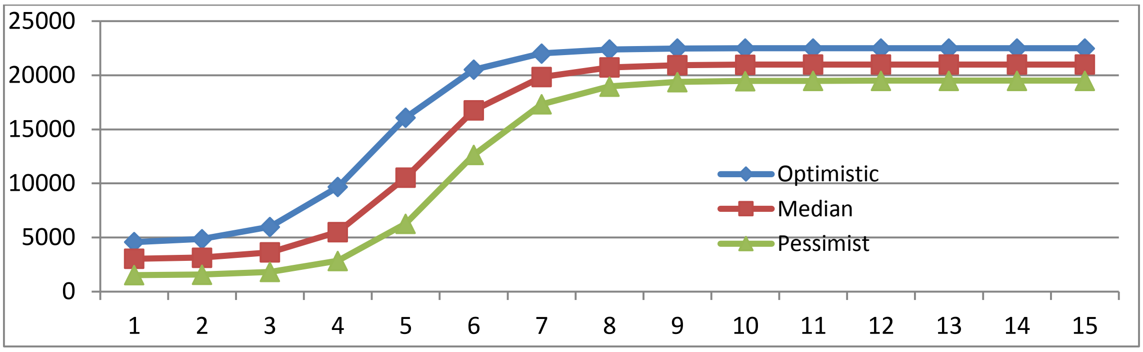


Figure 73 – Graphic perspective of number of clients along the years for Suburban scenario

5.5.3.2 Capex

To describing this scenario with a population distribution (near Head-End) and using the values calculated in section 4, the next table 34 and figure 74 present the capital costs associated with the implementation of the access network HFC over the next 10 years (the values of Capex in last 5 years of implementation are very low compared with previous investments):

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
9.180.231 €	487.520 €	1.800.022 €	5.158.289 €	7.928.299 €	4.879.530 €	1.489.251 €	328.922 €	83.386 €	8.659 €
5.317.858 €	176.251 €	659.663 €	2.313.170 €	5.505.484 €	6.030.246 €	2.752.739 €	709.348 €	158.098 €	38.355 €
2.687.475 €	1.977.502 €	774.399 €	2.441.862 €	4.885.664 €	5.521.474 €	3.231.051 €	1.008.506 €	231.408 €	47.627 €

Table 32 – Capex cost for Rural Scenario (•Optimistic; •Median; •Pessimistic)

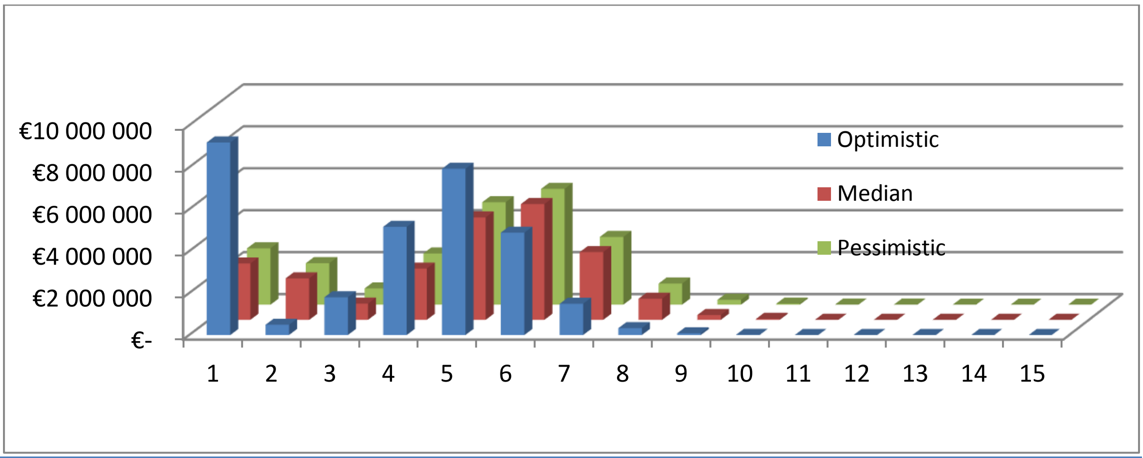


Figure 74 – Graphic representation of Capex to Suburban Scenario

5.5.3.3 Opex

The Opex is associated with the number of subscribers and a percentage of the capital costs. Using the formula 32, the operating costs for the suburban model are shown in the next table 35 and figure 75:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
1.467.660 €	1.457.503 €	1.685.858 €	2.547.471 €	3.971.514 €	4.787.330 €	4.883.192 €	4.736.670 €	4.550.256 €	4.368.097 €	4.201.911 €	4.051.827 €	3.916.668 €	3.795.007 €	3.685.507 €
895.651 €	873.448 €	947.647 €	1.352.765 €	2.440.450 €	3.670.266 €	4.149.751 €	4.150.242 €	4.025.059 €	3.883.378 €	3.748.825 €	3.626.210 €	3.515.649 €	3.416.097 €	3.326.490 €
450.682 €	628.265 €	691.300 €	1.011.246 €	1.845.186 €	3.050.305 €	3.782.786 €	3.910.242 €	3.819.594 €	3.686.334 €	3.554.375 €	3.433.591 €	3.324.351 €	3.225.942 €	3.137.354 €

Table 33 - Opex cost for Suburban Scenario (•Optimistic; •Median; •Pessimistic)

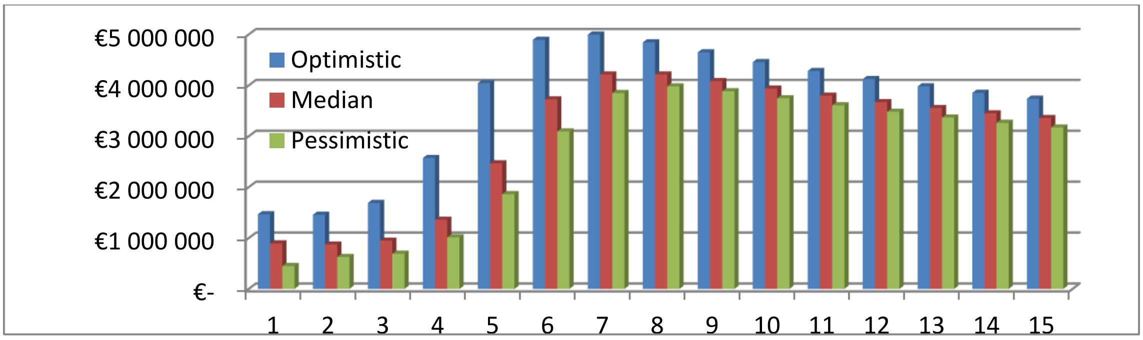


Figure 75 – Graphic representation of Opex to Suburban scenario

5.5.3.4 Revenues

The service available in the network is the triple play, as explained in chapter 3.5. (annual cost 450,00 €.). With the number of subscribers, the resulting calculations are presented in the next table 36 and figure 76:

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
2.290.155 €	2.354.394 €	2.816.348 €	4.414.722 €	7.122.110 €	8.811.748 €	9.170.033 €	9.045.400 €	8.807.456 €	8.550.507 €	8.295.568 €	8.047.043 €	7.805.705 €	7.571.550 €	7.344.407 €
1.364.495 €	1.372.122 €	1.535.096 €	2.259.311 €	4.204.689 €	6.475.008 €	7.437.025 €	7.536.429 €	7.384.691 €	7.179.478 €	6.967.639 €	6.759.378 €	6.556.763 €	6.360.096 €	6.169.301 €
682.254 €	686.186 €	769.890 €	1.168.002 €	2.501.973 €	4.881.151 €	6.492.799 €	6.894.983 €	6.834.128 €	6.661.623 €	6.468.859 €	6.276.329 €	6.088.371 €	5.905.792 €	5.728.634 €

Table 34 - Revenues for Suburban Scenario (•Optimistic; •Median; •Pessimistic)

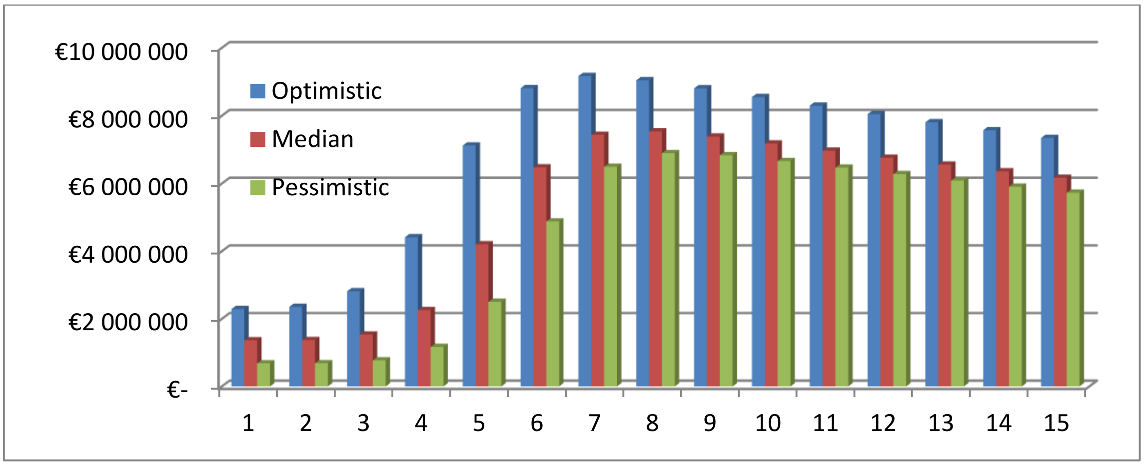


Figure 76 – Graphic representation of Revenues to Suburban scenario

5.5.3.5 Results

To complete the evaluation of the suburban scenario, the several factors were calculated (Cash Flow, NPV, IRR and Pay-back period) and the results in the table available on Appendix D.3 and figures 77, 78 and 79:

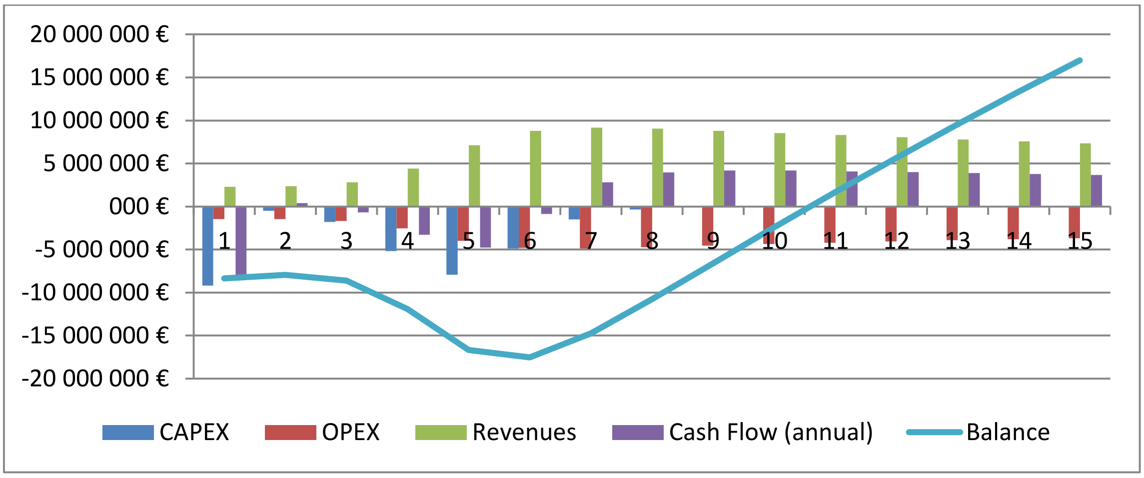


Figure 77 – Suburban scenario Optimistic Graphical Results

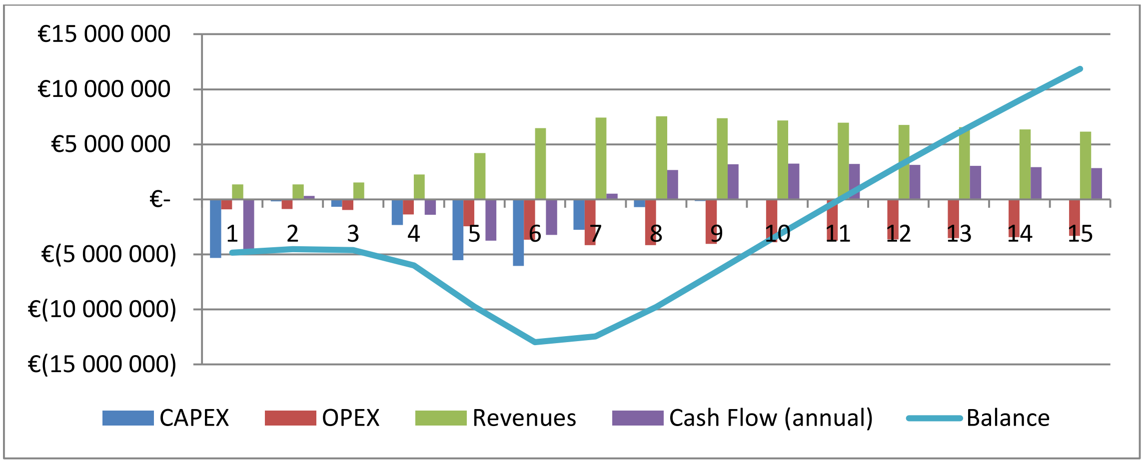


Figure 78 – Suburban scenario Median Graphical Results

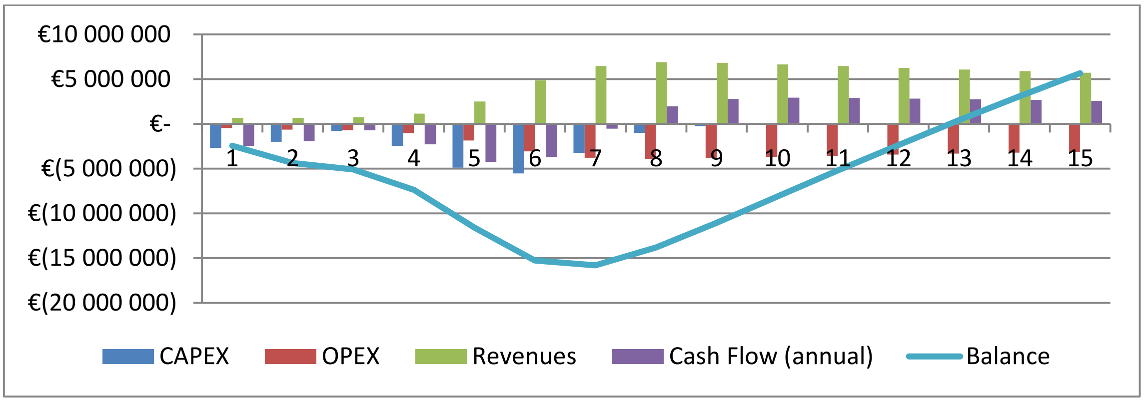


Figure 79 – Suburban scenario Pessimistic Graphical Results

5.6 Conclusions

Analyzing the results on the different scenarios of the implementation of the HFC networks, it is possible to draw the following conclusions:

Only the rural scenario does not present financial viability in the implementation, while the other two examples for any market penetration have positive balance at the end of the period. The urban scenario has a pay-back period of 7 years (median and optimistic) and 9 years (pessimistic), with much higher costs when compared with the suburban. This one has a more gradual investment and has a pay-back period around 11 years, but with excellent balance in the end. The figure 80 compares the 3 scenarios balance values for the median penetration:

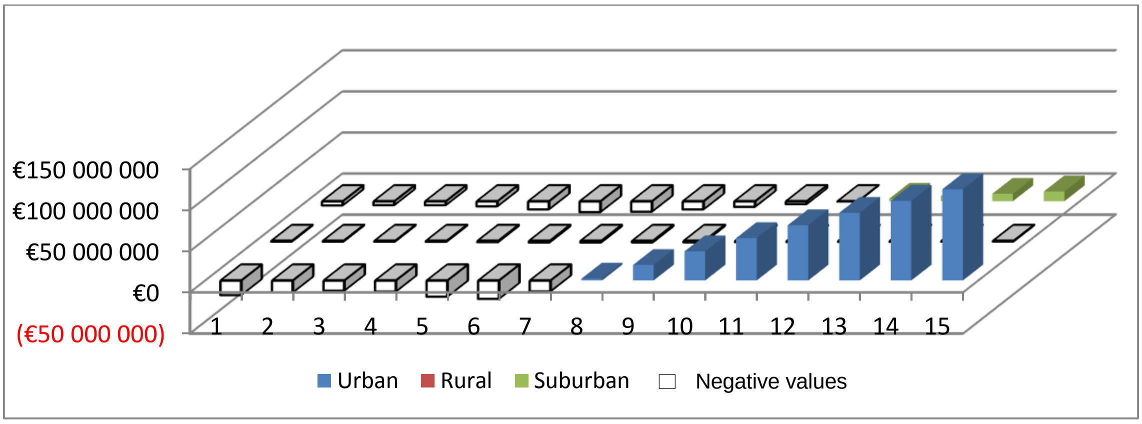


Figure 80 – Graphical representation of Balance values for the different scenarios

The Rural scenario has a very large area and a very low population density. By consequence the associated cost per home passed is quite high and at the end of 15 years the do return of the investment made doesn't happen.

The Suburban scenario has a gradual penetration, so the depreciation of the equipment prices lead to a lower Capex investment. Also with smaller number of subscribers revenues are lower when compared to the urban scenario. The population distribution decreases with the distance to the Head-End, implying that the last houses to be served are the most remote and that there is less compliance in the end, as the length of wiring is moderately constant throughout the years.

The Urban scenario is as expected the most profitable, with great profits and the lowest pay-back period. The high population density and a uniform distribution provide a faster implementation, with fewer infrastructures and less wiring length. The capital costs are mostly applied on equipment to cover all the subscribers. The revenues are higher and the results show an excellent viability for implementation.

As expected, the optimistic penetration present the best results obtained when compared to the remaining models of market penetration. Despite the slight increase in investment over the median and pessimistic penetrations, due to the higher cost of the material in the early years of the project and the superior value of OPEX, the final balance is presented clearly superior. This is, as was expected, the penetration with fastest growing number of customers when compared to other penetrations, generating higher revenues.

Although the final balances on optimistic penetration models are higher than the median, the IRR (for NPV> 0) shows a higher percentage value for the median case. This is due to the big initial investments of the optimistic model, that lead to very negative cash flows on the first years, making them high risk investments.

Finally the cost price per home passed is lower when compared to the model of full implementation in the initial year shown in section 4.1. The cost per home passed are visible if the next figure 81:

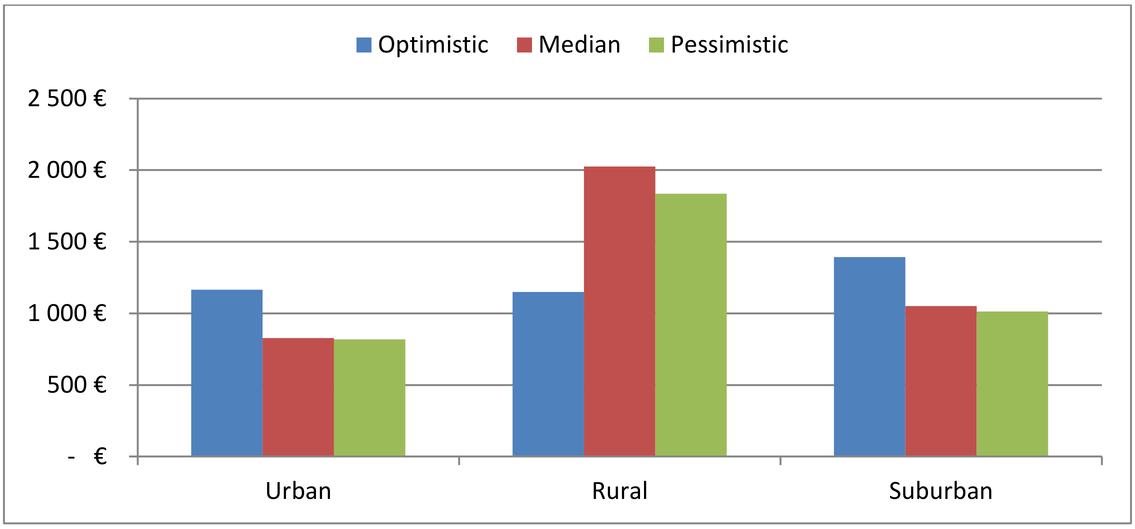


Figure 81 – Cost per home passed

6. Final Thoughts

To complete this work is exposed the main conclusions about the study finished. Some suggestions for future investigation that may continue the aspects covered in this dissertation are also stated.

6.1 Conclusions

The preparation of this dissertation focused on aspects of engineering and technical-economic analysis of HFC access networks. This study is motivated by the large resource consumption of TV and internet in daily life, making them into relevant factors for economical, cultural and social development of countries. With the current state of the European economy, the prices and quality of services available, led to a very competitive market among telecom companies. The small details began to have very significant influence on the service prices and originated a need for more detailed studies for the best investment approaches.

The companies expanded their business looking for new countries in need of new access networks, the undeveloped emerging countries. Countries such as China, Brazil, Angola, Dubai, etc ... show great growth, with high GDP, large public works and new job opportunities, which led to the arrival of many immigrants searching for a better life. These countries felt the need to develop and improve their life conditions. This development need showed an opportunity for the implementation of new access networks, which has been well explored by major telecommunications companies, through partnerships and the availability of technical and specialized managers.

With the proper economic analysis tool, this work began with the characterization of the state of the art HFC technology, its protocols, equipment and structure. After this evaluation, parameters were organized for network dimensioning (to determine the size and cost of the network, among others) based on the population distribution, a geographic and demographic analysis. Another element to the designed was the bandwidth necessary per CMTS to cover a certain number of subscribers, important to characterize the number of necessary equipments for a seamless service network.

After all design and parameter determination, the evaluation of the economic viability of this investment was performed, for three different types of scenarios: urban, rural and suburban. Considering the rate of penetration, the market available, the Capex, Opex and revenue generated, it is concluded that for some scenarios there is economic feasibility associated with the implementation of an HFC network.

Concluding a calculation tool was developed to perform the dimensioning of HFC networks and determines its economic feasibility, according to a set of inserted parameters. The objectives of this thesis have been, on the whole, successfully achieved.

6.2 Future Work

The objective of this dissertation was the dimensioning of new access networks, development of ways to deal with problems of spatial uncertainty and consumption of bandwidth by users in a specific area and a technical and economic assessment of the HFC network for the different type of scenarios was made.

For future work, some aspects are mentioned that could be approached in further studies to improve the calculation tools used such as:

• Taking into account the cost of power supplies for equipment used;

• Consider the lifetime of the equipment and investment for its replacement;

• More detailed analysis of the equipment to install and infrastructure, particularly within the Head-End;

• Consideration of fees as cost permissions of passage and possibility of renting infrastructure to third parties, namely the incumbent, vertically integrated;

• Regulations of Information and Communications Technology (ICT) for the implementation of new access networks in specific regions;

• Include sizing limitations and costs associated with power budgeting of equipment;

• Relate the limitations of CMTS bandwidth per CM, with market permeation evolution;

• Implementations conducted by private companies that lease lines to service providers;

• Take into account the existence of some infrastructure already implemented;

• Study of the cost associated with the implementation of other technologies specifically wireless, ones like (WiMAX or LTE);

• Addition of various types of service and study the socio-economic profile, to define specific services to distinct zones with different technological solutions;

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Appendix A – DOCSIS Bandwidth

The protocol chosen by DOCSIS, from the modulation schemes up to the networking protocols, presented in table 2. The lower four layers are specific to MSO (Multiple System Operator) cable data networks in which they are only present between the CM and CMTS. The higher-layer protocols, IP and above, are carried by the DOCSIS layers across the cable network and are used for communication with the Internet [60].

The physical layer protocol describes the modulation formats used on the cable network, on both the forward and reverse paths. The starting point for the design was to describe both the forward and return path channel models that are essentially the worst case RF channels for a DOCSIS cable data system. In the forward direction, the cable system is assumed to have a passband with a lower edge at 50 MHz and an upper edge, which is implementation-dependent but typically in the range of 300–860 MHz. Within that passband, NTSC analog television signals in 6-MHz channels are assumed to be present on either of the standard, HRC, or IRC frequency plans (EIA Interim Standard IS-6) as well as other narrowband and wideband digital signals. In the upstream direction, the cable system may have a subsplit (5–30 MHz) or extended subsplit (5–42 MHz) passband [19].

For the bandwidth model, we need to convert between the actual payload of the channel and the raw bit rate of the channel. The difference between these two bit rates is the overhead. The figure shows the overhead per packet in DOCSIS:

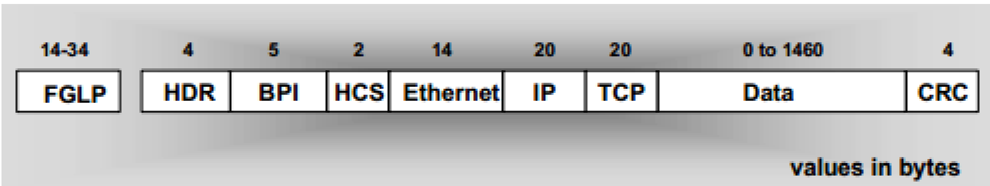

Figure 82 – DOCSIS per Packet Overhead

The bytes expression above FGLP refers to FEC, Guard Time, Last Code word, and Preamble. These values are unique to the upstream. The other fields are the DOCSIS header (HDR) and header checksum (HCS), baseline privacy (BPI). The bytes values shown are typical values [45].

The next table 37 shows the calculations for the overhead per channel for the downstream for 64 QAM and 256 QAM [45] [60]:

Region	**USA**		**Europe**	
Bandwidth (MHz)	6	6	8	8
Constellation size	64	256	64	256
Symbol Rate (Msps)	5,056941	5,360537	6,952	6,952
Alpha	0,186	0,119	0,151	0,151
Bits per Symbol	6	8	6	8
FEC Frame Sync	0,08%	0,05%	0,00%	0,00%
FEC Parity Bytes	4,69%	4,69%	7,84%	7,84%
Trellis Coding Overhead	6,67%	5,00%	0,00%	0,00%
MPEG Header	2,13%	2,13%	2,13%	2,13%
MPEG Pointer Byte	0,54%	0,54%	0,54%	0,54%
PHY Layer Raw BW	30,34	42,88	41,71	55,62
PHY Overhead	13,5%	11,9%	10,3%	10,3%
PDU Layer BW (Mbps)	**26,25**	**37,78**	**37,42**	**49,89**

Table 35 - DOCSIS Downstream Channel Overhead

The following table 36 presents the calculations for the per channel overhead for the upstream [45]:

Region	**USA**		**Europe**	
RF Bandwidth (MHz)	1,6	3,2	3,2	6,4
Alpha	0,25	0,25	0,25	0,25
Constellation Size	4	4	16	64
Symbol Rate (ksps)	1280	2560	2560	5120
Bits per Symbol	2	2	4	6
PHY layer BW (Mbps)	**2,56**	**5,12**	**10,24**	**30,72**

Table 36 - DOCSIS Upstream Channel Overhead

Appendix B: HFC Elements Costs

This section will show the element costs and the deductions required for a techno-economic analysis of the HFC network dimensioning. The price of the equipments for the first year is taken from a database provided by Professor Doutor A. Manuel Oliveira Duarte. The following table shows the respective initial prices and their evolution over 15 years, depending on their characteristics, as explained in section 3.4.3:

Price Evolution

Network	Component	Ripeness	K	Price Evolution															
				2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Head-End	Rack (Bastidor)	old,meduim	1,0	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50	720,50
	SubRack	old,very slow	1,0	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50	89,50
	Card OLT	emerging,very slo	0,7	3.606,27	3.408,26	3.221,14	3.044,33	2.877,24	2.719,35	2.570,15	2.429,16	2.295,94	2.170,06	2.051,12	1.938,73	1.832,53	1.732,20	1.637,40	1.547,83
	Port RF/WDM	new,slow	0,70	691,23	618,12	552,90	494,76	442,93	396,77	355,67	319,10	286,60	257,75	232,16	209,52	189,51	171,88	156,38	142,80
	Patchcord	new,medium	0,9	3,58	3,35	3,14	2,94	2,76	2,59	2,44	2,31	2,19	2,09	2,01	1,94	1,89	1,86	1,83	1,81
	Transition module	emerging,very slo	0,70	66,82	63,15	59,68	56,41	53,31	50,38	47,62	45,01	42,54	40,21	38,00	35,92	33,95	32,09	30,34	28,68
	Cable Router Managemen	emerging,medium	0,8	22.000,00	19.101,19	16.585,95	14.404,11	12.512,21	10.872,75	9.453,38	8.226,35	7.167,98	6.258,18	5.480,09	4.819,68	4.265,27	3.806,93	3.435,71	3.142,70
	Edge QAM Device DOCSI	emerging,medium	0,80	14.400,00	12.502,59	10.856,26	9.428,14	8.189,81	7.116,71	6.187,66	5.384,52	4.691,77	4.096,26	3.586,97	3.154,70	2.791,81	2.491,81	2.248,83	2.057,04
	CMTS DOCSIS 3.0	emerging,medium	0,8	25.920,00	22.504,67	19.541,27	16.970,66	14.741,66	12.810,07	11.137,80	9.692,14	8.445,18	7.373,27	6.456,54	5.678,46	5.025,26	4.485,26	4.047,89	3.702,67
	Fusion Model	old,meduim	0,90	183,19	177,81	173,80	170,92	168,90	167,53	166,61	166,00	165,60	165,34	165,17	165,07	165,00	164,95	164,92	164,90
Feeder Network and Distribution Network - Wiring and JFO	Cable 288 of	mature,medium	0,9	4.385,20	4.135,48	3.914,42	3.723,34	3.563,11	3.433,55	3.332,88	3.257,72	3.203,60	3.165,83	3.140,09	3.122,85	3.111,46	3.103,99	3.099,12	3.095,97
	Cable 96 of	mature,medium	0,90	1.933,26	1.823,17	1.725,71	1.641,47	1.570,83	1.513,72	1.469,33	1.436,20	1.412,34	1.395,69	1.384,34	1.376,74	1.371,72	1.368,43	1.366,28	1.364,89
	Cable 48 of	mature,medium	0,9	1.150,53	1.085,01	1.027,01	976,88	934,84	900,85	874,43	854,71	840,52	830,60	823,85	819,33	816,34	814,38	813,10	812,28
	Cable 24 of	mature,medium	0,90	773,30	729,27	690,29	656,59	628,33	605,49	587,73	574,48	564,94	558,28	553,74	550,70	548,69	547,37	546,51	545,96
	Cable 12 of	mature,medium	0,9	598,84	564,74	534,55	508,46	486,58	468,88	455,14	444,87	437,48	432,32	428,81	426,45	424,90	423,88	423,21	422,78
	Cable 6 of	mature,medium	0,90	542,26	511,38	484,04	460,41	440,60	424,58	412,13	402,84	396,14	391,47	388,29	386,16	384,75	383,83	383,23	382,83
	Cable 1 of	mature,medium	0,9	330,07	311,27	294,63	280,25	268,19	258,44	250,86	245,20	241,13	238,29	236,35	235,05	234,20	233,63	233,27	233,03
	Cable 1 of exterior	mature,medium	0,90	339,50	320,17	303,05	288,26	275,85	265,82	258,03	252,21	248,02	245,10	243,10	241,77	240,89	240,31	239,93	239,69
	Joint 96/144 of	emerging,very slo	0,70	323,22	305,47	288,70	272,86	257,88	243,73	230,36	217,72	205,78	194,50	183,84	173,76	164,25	155,25	146,76	138,73
	Joint 288 fo (JFO)	emerging,very slo	0,70	360,27	340,49	321,80	304,13	287,44	271,67	256,76	242,68	229,37	216,79	204,91	193,68	183,07	173,05	163,58	154,63
1st Point of Aggregation	Optical Node (NO)	new,slow	0,9	13.365,00	12.930,82	12.511,88	12.107,87	11.718,53	11.343,64	10.983,05	10.636,67	10.304,46	9.986,48	9.682,82	9.393,66	9.119,27	8.859,95	8.616,04	8.387,91
	ROM 12	emerging,very slo	0,70	661,00	624,71	590,41	558,00	527,37	498,43	471,09	445,25	420,83	397,76	375,95	355,35	335,89	317,50	300,12	283,70
	ROM 24	emerging,slow	0,7	781,00	697,59	623,12	556,61	497,23	444,21	396,87	354,61	316,88	283,21	253,17	226,36	202,44	181,11	162,10	145,16
	ROM 48	emerging,slow	0,80	1.502,00	1.399,54	1.304,09	1.215,18	1.132,37	1.055,24	983,41	916,52	854,24	796,27	742,31	692,11	645,41	601,99	561,64	524,16
	ROM 98	emerging,slow	0,8	2.554,00	2.379,77	2.217,47	2.066,29	1.925,48	1.794,33	1.672,19	1.558,45	1.452,55	1.353,98	1.262,23	1.176,86	1.097,45	1.023,62	955,00	891,28
	Cabinet 288 of (SRO)	new,slow	1,00	2.632,00	2.632,00	2.632,00	2.632,00	2.632,00	2.632,00	2.632,00	2.632,00	2.632,00	2.633,00	2.634,00	2.635,00	2.636,00	2.637,00	2.632,00	2.632,00
2nd Point of Aggregation	Distribution Amplifier	new,medium	0,8	428,00	372,20	323,98	282,42	246,74	216,28	190,48	168,90	151,15	136,86	125,67	117,17	110,91	106,45	103,35	101,25
	Pwr Splitter 1:4	emerging,slow	0,80	10,00	9,32	8,68	8,09	7,54	7,03	6,55	6,10	5,69	5,30	4,94	4,61	4,30	4,01	3,74	3,49
	Pwr Splitter 1:8	emerging,slow	0,8	20,00	18,64	17,36	16,18	15,08	14,05	13,09	12,20	11,37	10,60	9,88	9,22	8,59	8,02	7,48	6,98
	Pwr Splitter 1:16	emerging,slow	0,80	30,00	27,95	26,05	24,27	22,62	21,08	19,64	18,31	17,06	15,90	14,83	13,82	12,89	12,02	11,22	10,47
	8 Coax Cable	emerging,slow	0,8	7.000,00	6.522,48	6.077,65	5.663,30	5.277,35	4.917,89	4.583,13	4.271,40	3.981,16	3.710,97	3.459,51	3.225,53	3.007,89	2.805,53	2.617,48	2.442,81
	2 Coax Cable	emerging,slow	0,80	7.000,00	6.522,48	6.077,65	5.663,30	5.277,35	4.917,89	4.583,13	4.271,40	3.981,16	3.710,97	3.459,51	3.225,53	3.007,89	2.805,53	2.617,48	2.442,81
Drop Network	TAP 4	old,meduim	0,9	10,00	9,71	9,49	9,33	9,22	9,15	9,10	9,06	9,04	9,03	9,02	9,01	9,01	9,00	9,00	9,00
	TAP 8	old,meduim	0,90	20,00	19,41	18,98	18,66	18,44	18,29	18,19	18,12	18,08	18,05	18,03	18,02	18,01	18,01	18,01	18,00
	Cable Coax 2	mature,medium	0,9	7.000,00	6.601,38	6.248,51	5.943,48	5.687,72	5.480,91	5.320,21	5.200,22	5.113,84	5.053,55	5.012,45	4.984,94	4.966,75	4.954,83	4.947,07	4.942,03
	Cable Coax 8	old,meduim	0,80	7.000,00	6.572,44	6.262,46	6.044,20	5.894,25	5.793,20	5.726,07	5.681,91	5.653,07	5.634,32	5.622,16	5.614,30	5.609,23	5.605,95	5.603,83	5.602,47
	Router	new,slow	0,9	40,00	38,70	37,45	36,24	35,07	33,95	32,87	31,83	30,84	29,89	28,98	28,11	27,29	26,52	25,79	25,10
	Modem DOCSIS	emerging,medium	0,80	100,00	86,82	75,39	65,47	56,87	49,42	42,97	37,39	32,58	28,45	24,91	21,91	19,39	17,30	15,62	14,28
	Telephone IP	old,meduim	0,9	15,00	14,56	14,23	14,00	13,83	13,72	13,64	13,59	13,56	13,54	13,53	13,52	13,51	13,51	13,50	13,50
	Terminal STB	emerging,medium	0,80	55,00	47,75	41,46	36,01	31,28	27,18	23,63	20,57	17,92	15,65	13,70	12,05	10,66	9,52	8,59	7,86

Table 37 – Elements Cost over 15 years

Appendix C: TONIC model: Wire lengths

The TONIC model is a geometries calculation tool used for rectangular areas where the streets and roads represent a parallel or perpendicular organization between them. Described on TONIC deliverable 7(2002), where it is assumed a rectangular geographic area divided in small homogeneously distributed areas where the residential building are localized [62][63].

According to this methodology, the network dimensioning uses the average cabling length on each area to divide the total geographic region in segments of equal size, as shown in figure:

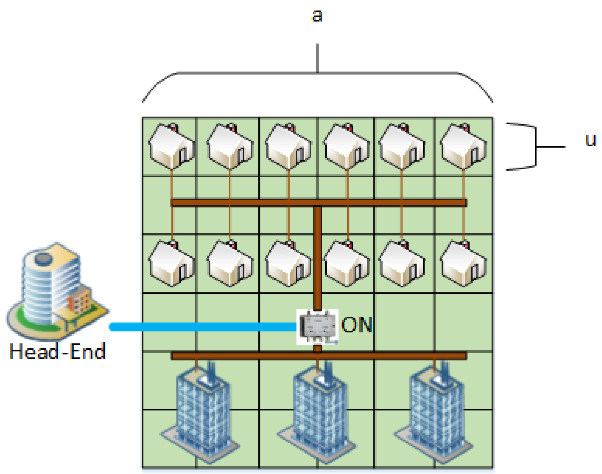

Figure 83 – Tonic geometric model

Each segment of the access network is further divided in n = a x a units, where each one represents one building to serve. The result is a square area of side $a=\sqrt{n}$. Each building has a fixed number of residences connected directly to the closest aggregation node [62].

This geometric terminology represented, using the same terminology of figure 58, the total length of the ducts is given by:

$$Id(a) = a^2 - 1 = u(n-1); \tag{39}$$

The following figure 84 illustrates the course of the wire between optical node and user home place:

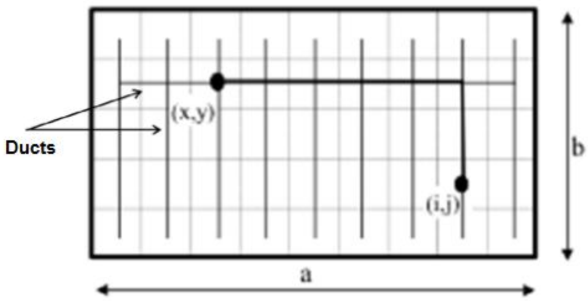

Figure 84 – Coordinates and course of the wire between optical node and user home place

Observing figure 84 and assuming again that the cabling follows the shortest path (only vertically or horizontally), on an area of length a and width b with the client territorial coordinates (i,), and the aggregation node coordinates (x,y),the total length of the fiber can be calculated as [63]:

$$Ic(a,b,x,y) = \sum_{i=0}^{b-1} \sum_{j=0}^{a-1} [|i-y| + |j-x|]; \quad (40)$$

where:

$x \in [0; a - 1]$;

y ϵ [0; b - 1].

Using Tonic Deliverable 7, it shows that the same formula can be expressed by:

$$Ic(a,b,x,y) = \frac{a}{2}[(b-y-1)^2 + y^2 + b - 1] + \frac{b}{2}[(a-x-1)^2 + x^2 + a - 1]; \quad (41)$$

Simplifying the equation:

$$Ic(a,b,x,y) = \frac{a^3}{2} = u \times \frac{n^{\frac{3}{2}}}{2}; \quad (42)$$

Appendix D

On this section is present the tables of results of the techno-economic analysis for the three scenarios.

D.1 – Urban Scenario

optimistic

Time (years)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
CAPEX	-33.716.243,47	-1.560.984,98	-5.713.422,87	-16.542.501,87	-25.513.733,17	-15.742.623,30	-4.771.707,52	-1.088.596,12	-217.642,32	-45.826,81	-9.168,49	-280,54	-58,68	-12,35	-2,62
OPEX	-5.809.102,57	-5.755.956,84	-6.536.545,76	-9.567.471,10	-14.637.496,47	-17.597.511,97	-18.000.311,80	-17.540.440,78	-16.922.827,24	-16.322.908,66	-15.773.273,25	-15.276.362,03	-14.828.818,28	-14.425.957,01	-14.063.365,88
Revenues	11.171.775	11.405.325	13.341.448	20.140.126	31.684.082	38.875.460	40.372.701	39.805.188	38.753.985	37.622.487	36.500.557	35.407.000	34.345.106	33.314.821	32.315.391
Cash Flow (annual)	-28.353.571	4.088.383	1.091.480	-5.969.847	-8.467.148	5.535.324	17.600.682	21.176.151	21.613.516	21.253.751	20.718.115	20.130.357	19.516.229	18.888.852	18.252.023
Balance	-28.353.571	-24.265.188	-23.173.708	-29.143.555	-37.610.703	-32.075.379	-14.474.697	6.701.454	28.314.970	49.568.721	70.286.836	90.417.193	109.933.423	128.822.275	147.074.298
Interest Rate (annual)	5,00%														
NPV	76.046.552,61														
IRR	21,33%														
Pay-back period	Year 7														

median

Time (years)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
CAPEX	- 21.219.635	- 501.559	- 1.916.147	- 6.694.156	- 15.995.918	- 17.589.758	- 7.928.396	- 2.070.989	- 452.469	- 79.024	- 25.754	- 1.324	- 136	- 29	- 6
OPEX	- 3.935.921	- 3.822.090	- 4.026.638	- 5.313.209	- 8.859.640	- 12.927.340	- 14.540.248	- 14.587.461	- 14.213.519	- 13.778.087	- 13.366.888	- 12.991.232	- 12.652.324	- 12.347.139	- 12.072.436
Revenues	7.558.158	7.526.260	8.119.545	10.966.538	18.715.024	27.768.998	31.575.273	31.922.057	31.262.731	30.390.362	29.492.876	28.611.171	27.753.503	26.921.042	26.113.442
Cash Flow (annual)	-17.597.398	3.202.610	2.176.760	-1.040.827	-6.140.533	-2.748.099	9.106.630	15.263.607	16.596.743	16.533.250	16.100.234	15.618.615	15.101.043	14.573.875	14.041.000
Balance	-17.597.398	-14.394.788	-12.218.028	-13.258.856	-19.399.389	-22.147.488	-13.040.859	2.222.748	18.819.491	35.352.741	51.452.975	67.071.590	82.172.634	96.746.508	110.787.509
Interest Rate (annual)	5,00%														
NPV	58.192.546,14														
IRR	23,68%														
Pay-back period	Year 7														

pessimistic

Time (years)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
CAPEX	- 14.123.633	- 6.645.392	- 2.674.730	- 8.163.053	- 15.200.751	- 15.320.896	- 8.244.821	- 2.495.821	- 578.161	- 123.616	- 24.639	- 4.894	- 251	- 53	- 11
OPEX	- 2.618.811	- 3.164.474	- 3.336.905	- 4.362.484	- 6.994.640	- 10.678.898	- 12.876.847	- 13.248.355	- 12.965.456	- 12.554.393	- 12.148.857	- 11.776.123	- 11.438.907	- 11.135.105	- 10.861.614
Revenues	5.026.866	4.966.430	5.203.695	6.607.615	11.479.800	20.225.173	26.129.833	27.556.932	27.270.943	26.573.257	25.802.297	25.033.915	24.284.129	23.555.872	22.849.253
Cash Flow (annual)	-11.715.578	-4.843.435	-807.939	-5.917.923	-10.715.591	-5.774.622	5.008.165	11.812.756	13.727.326	13.895.247	13.628.800	13.252.898	12.844.970	12.420.714	11.987.628
Balance	-11.715.578	-16.559.014	-17.366.953	-23.284.876	-34.000.467	-39.775.089	-34.766.924	-22.954.167	-9.226.841	4.668.407	18.297.207	31.550.105	44.395.075	56.815.789	68.803.417
Interest Rate (annual)	5,00%														
NPV	29.310.980,56														
IRR	13,91%														
Pay-back period	Year 9														

Table 38 - Results for Urban Scenario (Cash Flow, NPV, IRR and Pay-back period)

D.2 – Rural Scenario

optimistic															
Time (years)	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00	11,00	12,00	13,00	14,00	15,00
CAPEX	-1.205.569,94	-16.385,63	-173.689,31	-500.357,64	-750.721,49	-457.566,91	-146.057,74	-42.663,77	-12.588,20	-125,63	-26,01	-5,41	-1,13	-0,24	-0,05
OPEX	-175.279,79	-167.329,65	-183.873,29	-255.449,51	-372.773,69	-436.979,14	-441.162,19	-425.830,29	-406.774,64	-387.859,81	-370.709,96	-355.246,99	-341.324,07	-328.792,06	-317.512,95
Revenues	216.611	219.585	250.944	363.320	554.758	673.726	697.877	687.661	669.413	649.848	630.465	611.576	593.234	575.438	558.175
Cash Flow (annual)	-1.164.239	35.870	-106.618	-392.487	-568.737	-220.820	110.657	219.167	250.050	261.863	259.729	256.323	251.908	246.646	240.662
Balance	-1.164.239	-1.128.369	-1.234.987	-1.627.475	-2.196.212	-2.417.032	-2.306.375	-2.087.208	-1.837.158	-1.575.295	-1.315.566	-1.059.243	-807.334	-560.688	-320.027
Interest Rate (annual)	5,000000%														
NPV	-884.220,24														
IRR	-1,687672%														
Pay-back period	15,00														

median															
Time (years)	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00	11,00	12,00	13,00	14,00	15,00
CAPEX	- 750.072	- 7.855	- 49.880	- 194.513	- 496.804	- 514.354	- 236.963	- 80.258	- 4.870	- 3.151	- 58	- 12	- 3	- 1	- 0
OPEX	- 111.265	- 105.440	- 107.456	- 135.266	- 217.447	- 306.394	- 338.733	- 337.054	- 323.305	- 309.622	- 296.740	- 285.084	- 274.579	- 265.122	- 256.610
Revenues	126.902	126.116	135.035	178.912	298.807	438.956	497.733	502.869	492.409	478.653	464.514	450.626	437.118	424.006	411.287
Cash Flow (annual)	-734.435	12.821	-22.301	-150.867	-415.443	-381.791	-77.963	85.557	164.235	165.880	167.716	165.530	162.536	158.884	154.676
Balance	-734.435	-721.614	-743.915	-894.782	-1.310.225	-1.692.016	-1.769.980	-1.684.423	-1.520.188	-1.354.308	-1.186.592	-1.021.062	-858.526	-699.642	-544.966
Interest Rate (annual)	5,000000%														
NPV	-800.341,95														
IRR	-4,431429%														
Pay-back period	15,00														

pessimistic															
Time (years)	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00	11,00	12,00	13,00	14,00	15,00
CAPEX	- 383.188	- 198.797	- 56.029	- 185.385	- 403.319	- 466.803	- 248.497	- 92.212	- 35.343	- 485	- 101	- 21	- 4	- 1	- 0
OPEX	- 56.432	- 72.871	- 74.761	- 95.025	- 152.651	- 233.669	- 277.576	- 283.408	- 275.523	- 262.999	- 251.240	- 240.547	- 230.899	- 222.211	- 214.390
Revenues	63.395	62.822	66.615	87.549	159.457	288.293	375.362	396.603	392.654	382.644	371.551	360.488	349.691	339.205	329.029
Cash Flow (annual)	-376.224	-208.847	-64.175	-192.861	-396.512	-412.180	-150.711	20.983	81.787	119.160	120.210	119.920	118.788	116.993	114.639
Balance	-376.224	-585.071	-649.246	-842.107	-1.238.619	-1.650.799	-1.801.510	-1.780.527	-1.698.740	-1.579.580	-1.459.370	-1.339.450	-1.220.662	-1.103.669	-989.030
Interest Rate (annual)	5,000000%														
NPV	-1.032.837,54														
IRR	-9,509521%														
Pay-back period	15,00														

Table 39 - Results for Urban Scenario (Cash Flow, NPV, IRR and Pay-back period)

D.3 – Suburban Scenario

optimistic															
Time (years)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	-9.180.231,41	-487.520,18	-1.800.021,94	-5.158.288,87	-7.928.298,65	-4.879.530,40	-1.489.250,67	-328.921,62	-83.385,92	-8.659,22	-1.763,40	-72,14	-15,09	-3,18	-0,67
OPEX	-1.467.660,40	-1.457.503,36	-1.685.857,52	-2.547.471,16	-3.971.513,69	-4.787.330,38	-4.883.191,62	-4.736.670,47	-4.550.256,21	-4.368.097,46	-4.201.911,12	-4.051.827,01	-3.916.668,08	-3.795.006,56	-3.685.507,08
Revenues	2.290.155	2.354.394	2.816.348	4.414.722	7.122.110	8.811.748	9.170.033	9.045.400	8.807.456	8.550.507	8.295.568	8.047.043	7.805.705	7.571.550	7.344.407
Cash Flow (annual)	-8.357.737	409.371	-669.531	-3.291.038	-4.777.702	-855.113	2.797.591	3.979.808	4.173.814	4.173.750	4.091.894	3.995.144	3.889.022	3.776.540	3.658.899
Balance	-8.357.737	-7.948.366	-8.617.897	-11.908.935	-16.686.638	-17.541.750	-14.744.159	-10.764.351	-6.590.538	-2.416.787	1.675.107	5.670.250	9.559.272	13.335.813	16.994.712
Interest Rate (annual)	5,00%														
NPV	5.025.707,44														
IRR	8,83%														
Pay-back period	10														

median															
Time (years)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	- 5.317.858	- 176.251	- 659.663	- 2.313.170	- 5.505.484	- 6.030.246	- 2.752.739	- 709.348	- 158.098	- 38.355	- 6.680	- 180	- 38	- 8	- 2
OPEX	- 895.651	- 873.448	- 947.647	- 1.352.765	- 2.440.450	- 3.670.266	- 4.149.751	- 4.150.242	- 4.025.059	- 3.883.378	- 3.748.825	- 3.626.210	- 3.515.649	- 3.416.097	- 3.326.490
Revenues	1.364.495	1.372.122	1.535.096	2.259.311	4.204.689	6.475.008	7.437.025	7.536.429	7.384.691	7.179.478	6.967.639	6.759.378	6.556.763	6.360.096	6.169.301
Cash Flow (annual)	-4.849.015	322.423	-72.214	-1.406.624	-3.741.245	-3.225.505	534.535	2.676.839	3.201.534	3.257.745	3.212.134	3.132.987	3.041.076	2.943.991	2.842.809
Balance	-4.849.015	-4.526.591	-4.598.805	-6.005.429	-9.746.674	-12.972.178	-12.437.644	-9.760.805	-6.559.271	-3.301.526	-89.393	3.043.594	6.084.671	9.028.662	11.871.470
Interest Rate (annual)	5,00%														
NPV	3.461.558,77														
IRR	8,87%														
Pay-back period	11														

pessimistic															
Time (years)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	- 2.687.475	- 1.977.502	- 774.399	- 2.441.862	- 4.885.664	- 5.521.474	- 3.231.051	- 1.008.506	- 231.408	- 47.627	- 4.424	- 1.552	- 75	- 16	- 3
OPEX	- 450.682	- 628.265	- 691.300	- 1.011.246	- 1.845.186	- 3.050.305	- 3.782.786	- 3.910.242	- 3.819.594	- 3.686.334	- 3.554.375	- 3.433.591	- 3.324.351	- 3.225.942	- 3.137.354
Revenues	682.254	686.186	769.890	1.168.002	2.501.973	4.881.151	6.492.799	6.894.983	6.834.128	6.661.623	6.468.859	6.276.329	6.088.371	5.905.792	5.728.634
Cash Flow (annual)	-2.455.903	-1.919.581	-695.809	-2.285.106	-4.228.877	-3.690.628	-521.039	1.976.236	2.783.126	2.927.663	2.910.060	2.841.186	2.763.945	2.679.834	2.591.277
Balance	-2.455.903	-4.375.484	-5.071.293	-7.356.399	-11.585.276	-15.275.904	-15.796.943	-13.820.707	-11.037.581	-8.109.918	-5.199.858	-2.358.672	405.273	3.085.107	5.676.383
Interest Rate (annual)	5,00%														
NPV	-720.622,83														
IRR	4,20%														
Pay-back period	12														

Table 40 - Results of Suburban Scenario