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Cost-effective deployment strategies for the rural FTTH roll-out

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Declaration

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Abstract

The main topic of this dissertation revolves around the problem of rural fibre-to-the-home (FTTH) service roll-out. The problem has become topical worldwide, typically in the countries with rural populations scattered around. Nevertheless, the FTTH service penetration rate generally remains low, which still creates room for research and innovation, whereby the planning of FTTH network deployment and roll-out can be advanced. In fact, the rural FTTH roll-out problem falls into category of worst-case scenarios, thereby driving technological progress to an even higher extent.

Inadequate future-proof broadband service in rural areas leads to negative consequences, widely known as the Digital Divide problem. Unequal development of urban and rural areas deepens the isolation of rural areas from the information society. The resolution of the problem is thus of great importance, also beyond purely technical outcomes. In fact, this work evolves beyond technical aspects and includes recommendations for local governments, policy regulators, investors, utility companies, and other likely contributors.

The first half of this work presents the following content. The background to the cutting-edge broadband technologies was presented with regard to the ultimate success of rural fibre roll-out. The discussion focused on one of the most promising future-proof broadband technologies with regard to the rural case, i.e. Passive Optical Network (PON) or long-reach PON (LR-PON) technology. A number of deliberations targeted the statement of the problem, research questions and hypotheses, and finally the research methodology. Key aspects of the problem were further explored. The literature review focused on the state-of-the-art means and deployment technologies, in different localities worldwide, and suitable mathematical formulations needed to model and optimise the deployment. Finally, research gaps were identified, and detailed research plan was proposed.

The increased deployment cost with respect to expected revenue is overall perceived as the main barrier to FTTH roll-out in rural areas. This provided grounds for the quest towards more cost-effective deployment strategies.

The second half of this work, therefore, focuses on researching the cost-effectiveness of deployment strategies for rural FTTH roll-out. The research was confined to the examination of the access section of LR-PON architecture. In fact, the deployment of this part can be classified as one of the most challenging and urgent issues in the rural FTTH roll-out problem. The examination of LR-PON roll-out happens top-down, in the following scopes.

Firstly, a potential nationwide deployment of Optical Distribution Network (ODN) section of 1024-way-split LR-PON in Ireland undergoes examination. The analysis is carried out to assess the effect of different optical power splitter arrangements of PON tree-like topology on the cost-effectiveness of the deployment, i.e. the utilisation of PONs, and the total amount of fibre cable length. A heuristic is used, and hierarchical clustering algorithm proposed with a simplified design, i.e. the Euclidean distance is used to serve as the proximity function in the clustering routine. The research findings and numerical

results were discussed. As a result, further improvements to maximise the utilisation of PONs and more advanced deployment models were discussed.

Secondly, a specialised Integer Linear Programming (ILP) model devoted to the rural FTTH deployment and the optimisation of the initial setup cost is proposed and evaluated. This model allows to cover a real-world deployment scenario of PON architecture and includes a number of important details into the design. Therefore, a least cost solution can be approached, also by taking into account actual equipment pricing and real geographical coordinates. Key features of the model include the use of multi-fibre blown cables, low-count power optical splitters, and street-map data set. Evaluation and tests target various rural areas in Ireland. A single test scenario corresponds to an area covered by a cabinet, which refers to a common migration scenario where fibre-to-the-cabinet (FTTC) represents an intermediate step towards FTTH. It was shown that by employing small optical power splitters near the locations of end-users, the size of feeder fibre cable decreases, thus significantly improving the initial investment fibre cable cost in excess of 25%.

Thirdly, the study adds a relevant perspective into the planning. The dynamism of network growth is included through the techno-economic examination of an important variable, i.e. the service take-up rate. This allows to demonstrate how the problem is further exacerbated by the uncertainty associated with end-users take-up rate. The randomness bound up with the subscribers service take-up imposes fluctuation and escalation in the total cost of deployment, and affects the outcome of the quest for cost-effective deployment strategies.

This part of work focuses on the following trade-off: (I) achieving optimal long-term deployment cost, but assuming a known expected take-up rate (due to optimal resource utilisation and sharing) versus (II) sacrificing some optimal resource management, in order to reduce short-term network up-front cost, which reduces the risk associated with lower than expected take-up rate.

The author believes that achieving objective (II) is generally key to succeed in rural areas. Moreover, building a network with the lowest up-front cost is critical to approach the viability of the network operation. Indeed, while the first approach (I) has been considered for denser areas, where the favourable economics allow for larger margins in take-up rate uncertainty, this work indicates that the second approach (II) implemented through the deployment strategy proposed herein, is generally preferable for rural roll-out. The numerical results show that the up-front cost can be slashed at the early stage of the FTTH network development.

The quest led to deep insight into rural FTTH deployment economics, thereby helping to identify these circumstances under which the deployment can be commercially viable. This could not occur, however, without the application of deployment strategies primarily designed to alleviate and deal with the rural FTTH deployment problem. These methods were mathematically formulated to instantiate a suite of clustering algorithms underpinning the cost-effectiveness and automation of the deployment strategies proposed in this work. Overall, this work proved that rural FTTH roll-out case requires special consideration, and novel network design strategies can further mitigate the problem.

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List of Acronyms

FTTH fibre-to-the-home

PON Passive Optical Network

LR-PON long-reach PON

OLT Optical Line Terminal

TPON Telephone PON

GPON Gigabit PON

CO Central Office

CAPEX Capital Expenditures

OPEX Operating Expenditures

FTTC fibre-to-the-cabinet

FTTB fibre-to-the-building

FTTP fiber-to-the-premises

ODN Optical Distribution Network

AWG Arrayed Waveguide Grating

ONU Optical Network Unit

ILP Integer Linear Programming

DSL Digital Subscriber Line

ADSL Asymmetric Digital Subscriber Line

VDSL Very High Bitrate Digital Subscriber Line (DSL)

DOCSIS Data Over Cable Service Interface Specification

NG-PON2 Next-Generation PON 2

XG-PON 10G-PON

XGS-PON 10-Gigabit-capable symmetric PON

D-side Distribution side

E-side Local Exchange side

ICT information and communication technologies

WiMAX Worldwide Interoperability for Microwave Access

DSLAM Digital Subscriber Line Access Multiplexer

EDFA Erbium-Doped Fibre Amplifier

SOA Semiconductor Optical Amplifier

IT Information Technology

NPV Net Present Value

IPTV Internet Protocol television

VoIP Voice over Internet Protocol

TWDM-PON Time and Wavelength Division Multiplexed PON

WDM-PON Wavelength Division Multiplexed PON

EPFU Enhanced Performance Fibre Unit

SFU Single Family Unit

MILP Mixed Integer Linear Programming

GPS Global Positioning System

BFT Blown Fibre Tube

BFU Blown Fibre Unit

CCP Capacitated Clustering Problem

NP-hard nondeterministic polynomial time

CPCC cost per customer connected

DIR duct installation rate

1 Introduction

The rural broadband roll-out problem has been repeatedly brought to the public attention, and regardless of the devoted efforts, it still merits a more thorough investigation. An account of ongoing changes in the market of broadband access networks serves the identification of key trends and ground-breaking technology advances. Since present-day technologies will become obsolete in the long run, early recognition of their limitations aids the assessment as to which technology fits the rural broadband roll-out the most in a long-term perspective. Also, the most promising technologies suitable for rural roll-out are being considered and examined for the attributes allowing for the ultimate success of rural fibre roll-out. The initial discussion revolves around the cutting-edge technologies offering the ultimate broadband services such as PON or LR-PON technology. After that, the discussion becomes intentionally directed towards the central theme of the thesis and in fact, one out of the most promising technologies. A subsequent outline focuses on foregone technology, and demonstrates an advanced architecture designed to provide optical access networking capability and infrastructure for optical access networks. The system can support (up to) 1024 end-users through a single, bare optical access network. Moreover, it is capable of reaching very remote rural end-users scattered beyond 100 km distance; and although every technical aspect plays significant role altogether, the other qualities of the problem and its broader context should not be certainly underestimated.

There is no doubt that problems that are well-defined are also simpler to be comprehended and solved, especially when they are complex and complicated. For that purpose, the problem statement has been enclosed next and intended for showing a deeper insight into the underlying issues occurring in the scope of rural roll-out problem. The statement has been interleaved with a description of the motivation behind the efforts devoted to address the problem and figure out such kind of a solution that is both effective and sustainable. Furthermore, such sort of review regarding the most problematic aspects of the problem creates an ideal bridge to the subsequent chapters. As a positive result of that, the literature can be examined more effectively for the lack of coverage or for the presence of research gaps, which leads to the identification of the areas that have been indeed overlooked, neglected or completely unexplored.

1.1 Background information

This section serves to first describe the current trends in the market of broadband technologies, with the special focus on fibre-to-the-home (FTTH) technology. Then, it compares different wired broadband technologies that could be potentially used for roll-out in the rural case. This serves to describe the drawbacks of other technologies compared with FTTH technology. Final purpose of this section is to introduce passive optical network (PON) technologies and summarise the reasons as to why long-reach PON (LR-PON) can be considered as one of the most promising candidates for rural FTTH roll-out.

1.1.1 Current trends in the market of broadband technologies

In the past decades, telecommunication operators have rested their deployments of broadband access networks predominantly upon the copper-based hardware or infrastructure, and therefore, technologies such as DSL or Asymmetric Digital Subscriber Line (ADSL) have dominated the market for a long time. The trend has changed, since the fibre access technology was introduced. Fibre-based access networks have demonstrated to be of great value to the global economy, and the situation in the global market of access networks have also overturned. Analysis [2] summarises the actual market share between a few major participants, and it provides a forecast for upcoming years. Abbreviation FTTx in [2] refers to Fibre-to-The-X where multiple terms can substitute x. It can either denote the fibre to the home (FTTH), which is a common dwelling unit in the rural scenario, or else, X can denote a building (fibre-to-the-building (FTTB)), which represents a typical dwelling unit in the urban scenario. Work [2] indicates a deep decline in the total number of subscribers that rely on fixed broadband DSL/ADSL technology. In turn, fibre - FTTH/P/B (”fibre-to-premises/building”) - gains the top position in analysis in [2]. In addition, FTTH/P/B technology is more frequently adopted for completely new deployments.

1.1.2 Evaluation of FTTH versus other wired broadband technologies

Fibre technology brings a solution that overcomes the major limitations of copper-based technology such as Very High Bitrate DSL (VDSL) or G.fast. More importantly, fibre technology is regarded as the most cost-effective candidate, which can sustain the constantly increasing end-user demands for higher data rates. It also ensures that achieving the ultimate bandwidth over long distances is both feasible and very economical. Those attributes are truly vital to the success of rural FTTH roll-out. A ground-laying study has arrived at an interesting conclusion made for Australian rural areas [3]. The findings show that FTTH defeats other opponents in the rural case provided that a higher data rate is required for demanding TV services. This happens in particular circumstances, i.e., when the density of end-users in the area under investigation falls below a specific threshold. Aside from all of that, the operating cost of a fibre-based network is relatively low. For that purpose, telecommunication operators are inclined towards forcing the closure of old copper-based networks in place of optical outside plants

[4]. Far more advantages could be listed. The symmetric bandwidth is another one noteworthy. It enables symmetric data rates both in upstream and downstream directions. Interestingly, the demand for high-speed upstream data rate grows in rural communities, e.g., in the case of e-medicine and remote animals treatment.

Nonetheless, the networks involving FTTC/VDSL or cable technology will not vanish immediately - [2] provides a prediction of that. Still, they remain competitive as they support gigabit data rates, in the latest standards, i.e. G.fast and Data Over Cable Service Interface Specification (DOCSIS) 3.1, respectively. Moreover, DOCSIS 3.1 standard also provides support for symmetric bandwidth. Despite all of that, major limitations persist. G.fast offers high-speed broadband yet over relatively short "last mile" loop links, as depicted in [5]. Similarly, cable technology has major drawbacks. One of the major downsides stem from the fact of sharing the bandwidth among a group of end-users, and thus, reducing overall performance during traffic peak hours. Also, cable service can not be unbundled, so that a negative effect endures and competitiveness among cable operators fails. Cable-based networks are widespread in the U.S., mainly in urban areas, but they are seldom deployed in digital-divide rural regions. Such a standstill situation has roots in high network deployment cost. Essentially, a new cable network would involve the installation of new dedicated coaxial cables since the existing copper links are unsuitable for that purpose. On the other hand, "last mile" copper loops can be reused for implementing networks with G.fast standard; hence, operators may still consider a migration step towards FTTH through an interim step, i.e. FTTC/G.fast - such a scenario is illustrated in [6].

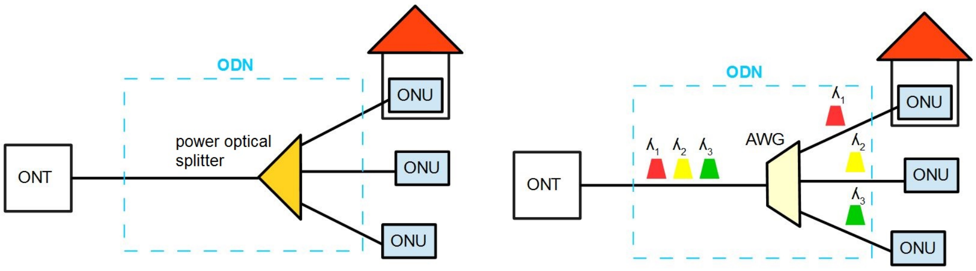
1.1.3 Passive optical network (PON) technology

The term FTTx or FTTH is broadly accepted in mass media and in scholar studies. In this work, however, a more technical term is preferred, i.e. passive optical network (PON).

The purpose of this section is to describe basic PON architectures and relevant terminology. Another goal is to highlight the main directions in the evolution of PON technology and showcase the cost savings resulting from the upgrade to more advanced PON architectures.

1.1.3.1 Basic PON architectures

PON has become a key technology that underpins both urban and rural FTTH roll-outs. PON is more advanced than point-to-point fibre deployment because it brings about significant savings. Such a significant decrease in the cost of deployment is due to the use of optical passive decoupling devices. As a result of that, Optical Line Terminal (OLT) card can be shared among hundreds of end-users (Optical Network Units (ONUs) or ONTs) over a single fibre feeder link, as sketched in Fig. 1.1. The figure depicts two kinds of optical distribution networks (ODNs), both varied with different passive decoupling devices, i.e. power optical splitter and Arrayed Waveguide Grating (AWG), respectively. A hybrid ODN combines those two kinds of devices, but it has been covered in the next section 1.2 - a section concerning more advanced architectures.



(a) power optical splitting (b) arrayed waveguide granting (AWG)

Figure 1.1: Optical distribution networks (ODNs) varied with different kinds of passive optical devices

1.1.3.2 The evolution of PON technologies

The progress of passive optical network technology continues. The advent of Telephone PON (TPON) [7], PON and Gigabit PON (GPON) [8] was nothing more but the auspicious commencement. Next, the effort was devoted towards standardisation and the accomplishment of higher data rates within the work on 10G-PON (XG-PON), Next-Generation PON 2 (NG-PON2) and 10-Gigabit-capable symmetric PON (XGS-PON) standards. At the moment, the work on 25G PON progresses and further standardisation targets 50 and 100 Gb/s PONs.

The most recent studies also concern the cutting-edge long-reach PON technology (LR-PON) [9]. The most advanced PON solutions allow reaching longer distances while handling relatively more end-users. The outcome of both, i.e. extending the reach of PON and increasing its split, has a positive effect on the economics of FTTH roll-out. FTTH becomes a more viable solution, and it grabs a higher market share. The following illustration shows the actual gains of using PON in a real-world deployment.

1.1.3.3 Showcase of an upgrade to Super-PON technology

This showcase occurs in an urban scenario. The economy in urban areas is commonly robust, and therefore, the take-up rate of FTTH service is anticipated to reach high figures in those areas. In other words, PON infrastructure is often in place there. Such environment forms an ideal setting for new studies to flourish. The study that was carried out in a mid-sized U.S. metropolitan area showcases a network upgrade and migration to more advanced architecture named Super-PON [10].

The upgrade replaces a short-reach GPON network with a long-reach Super-PON network, leading to a variety of savings. First of all, the amount of Central Offices (COs) equipped with active equipment could be slashed down significantly. Moreover, 12-48 fibre cables have simplified the deployment process, and superseded the large 432-fibre cables. This, in turn, enabled low-cost deployment with the employment of micro-trenching technique. Small-size cables also help to reduce the cost of repairing.

1.1.4 Reasons to consider long-reach PON (LR-PON) for rural FTTH roll-out

PON represents a completely passive optical network except for OLT and ONU/ONT devices which are in fact active, i.e. electrically powered devices. Consequently, the lack of active equipment in the ODN section of the FTTH network makes PON technology even more promising and cost-efficient. Also, PON standards support high data rates, and it was elaborated above. Furthermore, the economic efficiency of PON-based deployment can be easily noticed in the rural scenario which exhibits sparse population of end-users to be covered and long distances to be reached between them. Overall, PON is viewed as the most promising future-proof broadband technology for FTTH roll-out in the rural scenario [3, 4].

A novel architecture, which increases the reach of standard GPON, has been proposed and demonstrated in rural Australia [11], [12]. This research reports several profitable outcomes. On the whole, access to broadband service could be provided to 99% of the population in the rural that was investigated. Also, the adequate provision of capacity for bandwidth-greedy multimedia services was reported. At the same time, network OPEX and maintenance cost were expected, and in fact engineered to remain at low levels. Moreover, a significant reduction in the number of rural COs resulted from the use of long-reach PON, lowering the cost of deployment further. Authors of this study adopted long-reach PON (LR-PON) term for their scheme and dedicated their solution specifically to deployment in remote and rural areas.

This dissertation centres around the LR-PON [13] architecture. This offers increased physical split-up rate of an optical signal, right up to 512 end-users. The maximum defined logical split-up in the specification of the protocol is even higher, and it amounts to 1024 end-users. Furthermore, the reach of LR-PON goes beyond 100 km, crossing the 60 kilometres limit of extended-reach GPON [12]. This novel LR-PON design enables even higher long-term savings than were possible before. First of all, the total number of OLT cards diminishes due to increased split-up rate (512-way-split versus 64-way-split). The total amount of fibre cables decreases due to an increased number of stages of optical power splitters in ODN design. With the aid of longer-reach beyond 100 kilometres, an initiative leading to a massive drop in the number of COs (local exchanges) could be in fact launched and implemented [13].

1.2 Outline of the long-reach PON (LR-PON) architecture

The purpose of this section is to describe the technology that remains the main topic of this thesis. The outline serves to describe different sections of LR-PON architecture and also to indicate on which particular section of LR-PON network this thesis focuses on. Also, it serves to describe LR-PON network's topology by illustrating how to leverage the split/reach of LR-PON in rural areas depending on the density of a rural area. Overall, the purpose of this section is to offer a conceptual foundation for further research such as that regarding the formulation of clustering algorithms in Chapters 4, 5 and 6.

FTTH roll-out may diverge in a multitude of ways, which strictly pertains to an architecture con-

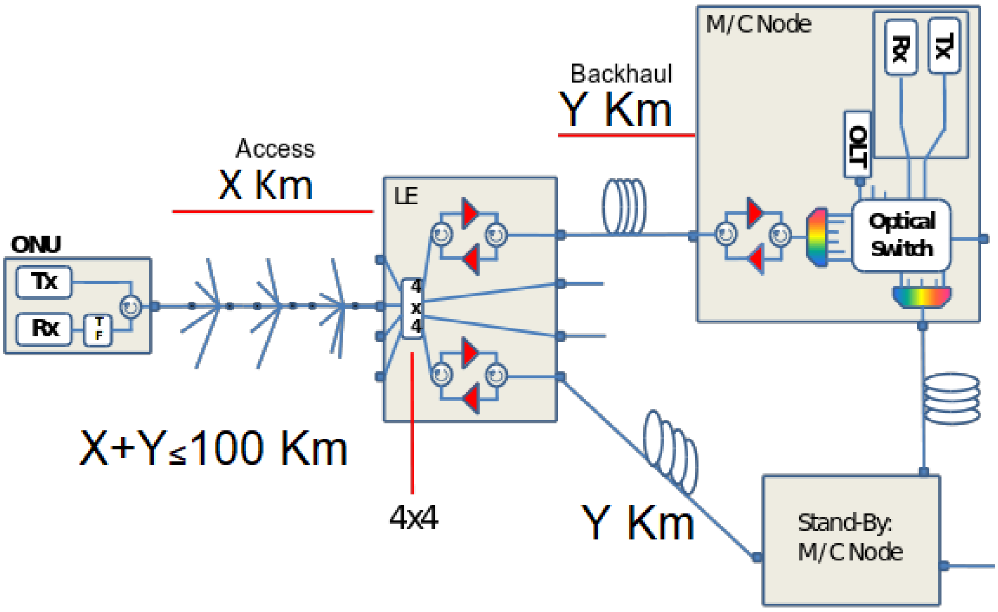


Figure 1.2: The outline of Long Reach PON architecture (the backbone network was not shown) [1]

sidered for the deployment. A brief survey on several extended-reach PON architectures is available in the reference work [10]. While the central goal of this thesis did not consist in comparing the performance of different long-reach PON architectures, the author of the thesis concentrate next on particular LR-PON architecture [9], and presents an outline for it in Fig. 1.2. It encompasses metro, amplifier and ONU nodes interconnected through the backhaul section of LR-PON and through the access section of LR-PON. In fact, the metro nodes are also interconnected through the backbone network. However, that part of LR-PON remained beyond the scope of this work, and it was intentionally omitted. Besides, the backhaul portion of LR-PON was already addressed and studied on many occasions [14, 15]. The primary focus of this thesis was directed towards the access part of LR-PON, and accompanying motivation for that is described in section 1.4. The extended reach in the LR-PON is sustained with the use of an amplifier node that accommodates optical amplifiers [13]. By moving the position of the node, we can vary the reach of access and backhaul links. In fact, the reach of the access section could be extended so that amplifier nodes can be consolidated in a common location, and the total number of active COs could be thus reduced. This constitutes a separate problem, which remains beyond the scope of this work.

Fig. 1.3 describes in detail the access portion of LR-PON. An amplifier node (e.g. located in a local exchange building) accommodates the first stage splitter (4:4), and 128-way-split PONs branch off, and they reach up to 10 kilometres. By varying reach and split, remote end-users can be reached up to 20 kilometres (with 64-way-split PON), and remote end-users up to 30 kilometres (with 32-way-split PON), and so forth. Controlling the LR-PON's split during its architecture design [9] allows varying the PON's both capacity and reach to serve smaller and more remote customer clusters, which is exactly

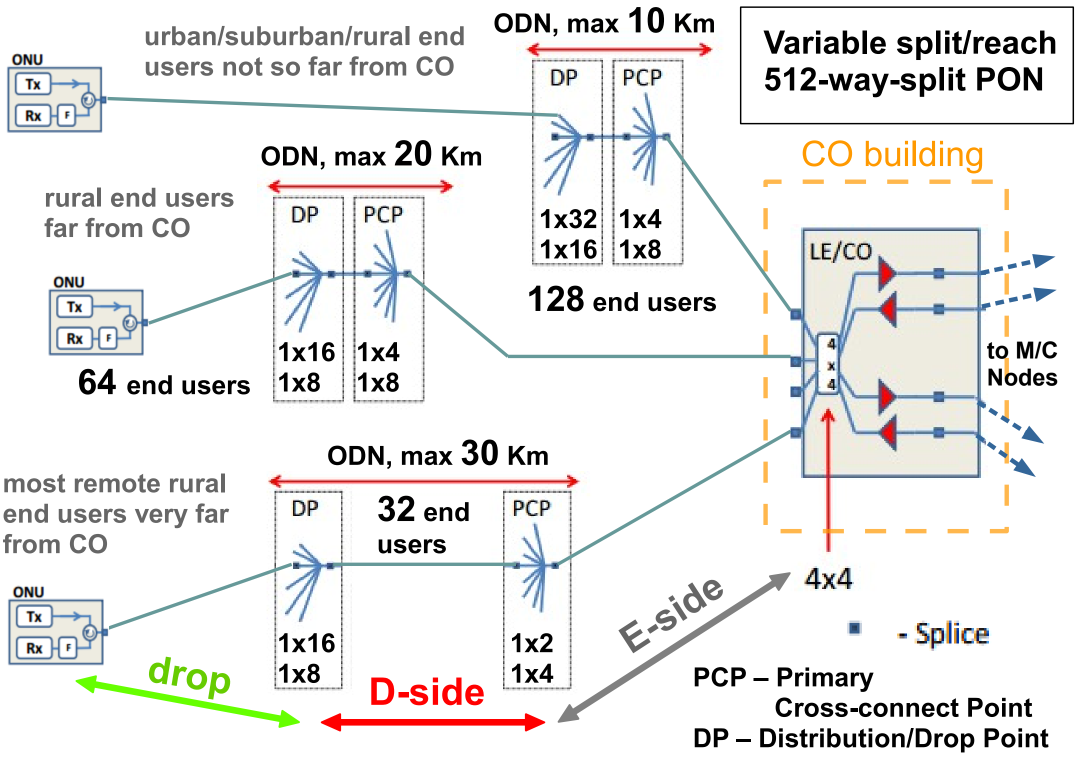


Figure 1.3: The access section of LR-PON: variable split/reach 512-way-split PON (original figure's source: [1])

the requirement in rural FTTH deployment. Moreover, multi-power OLT cards could be considered to vary LR-PON reach, however, to avoid the implied increased management complexity, the idea was not considered.

In addition, to describe particular sections of the access network in Fig. 1.3, the terminology used in British Telecom materials (examine [6]) was employed, i.e. the drop, the Distribution side (D-side), and the Local Exchange side (E-side) sections. For the E-side section, different cabling was considered, i.e. more robust and more expensive. The author of the thesis intentionally highlighted the drop and D-side sections in the figure because the highest savings and fibre cable aggregation can be obtained within the scope of those sections, i.e. in the closest proximity to end-users.

1.3 Deliberations

The main goal of this section is to discuss the following topics. Firstly, the aim is to define and describe rural FTTH roll-out problem. Next subsections serve to formulate and deliberate on research questions and hypotheses. Then, the research methodology is proposed and discussed. The methodology will be used to test hypotheses and to address research questions.

Final purpose is to conclude this long deliberations with a single main research question and a number of relevant specific research questions. This also servers to determine the title of this thesis.

1.3.1 Problem statement

The main topic of this dissertation relates to the rural FTTH roll-out problem. The problem has become topical worldwide for a wide range of regions and countries inhabited with sparse rural populations although it has been addressed in various ways. The foregone lack of FTTH service in rural areas surely leaves spare room for much of innovation and research opportunities. The act of researching the topic is indeed important due to a variety of reasons. The rural roll-out falls under a broader category, namely, FTTH brings about the ultimate broadband services which are as essential for rural communities as for urban communities. Also, not everyone immediately discerns the criticality of fibre access networks in relation to many spheres, ranging from economic to social, of everyday life. The lack of adequate broadband services in rural areas yields severe consequences in turn, leading to digital divide problem and unequal development of areas isolated from the rest of modern and vital society. Thus, the action of providing a suitable resolution is of great importance also beyond purely technical outcomes. On the other hand, the problem involves a broad spectrum of technical challenges, problems, sub-problems and issues worth being examined and addressed. In fact, the rural roll-out problem represents a form of a worst-case scenario, thereby driving technological progress to a higher extent, in contrast to less demanding scenarios.

It is the worst-case from the economic perspective, yet for another reason, i.e. the dynamism in the number of end-users in the network, whereas this parameter is typically static in the urban case.

The presence of a vast problem area translates into an excessive number of research questions, and a sort of delineation is indeed required. This delimitation narrows down the sum of our intentions declared in the course of this dissertation. The first question of this thesis does not delve into the details of the problem, yet it concerns the rural FTTH roll-out as a whole. The intention of the author of this thesis is to gather and then look into a wide range of barriers hindering the roll-out, and carry out the same activity for the opposite force, i.e. drivers facilitating the roll-out. Such an enquiry underpins our next intention, i.e., the author of this thesis aims to devise a holistic research framework rather than focus solely on particular qualities of the problem. Ideally, a comprehensive overview of the problem should allow to extract sub-problems from a broader context, and then allow to understand interrelationships among them. In this way, a schedule for sub-problems could be next arranged to determine which of them should be solved either independently or sequentially. Such a holistic approach bears certain qualities for solving complex problems. It serves the identification of root difficulties, the prioritisation of sub-problems and the quantification of their variability in various localities globally. In addition, by providing a wider insight into the problem, potential contributions can be next expected from a larger number of contributors or directions.

The rural FTTH roll-out problem can be classified as highly complex and complicated. The problem is complex because:

- it is comprised of many elementary parts, and it relates to various research domains. In other words, it contains a number of constituent major sub-problems, which also involve a larger number of constituent sub-problems or issues;
- it involves all manner of trade-offs;
- the contributions can be pursued from very various perspectives;
- there is no single solution to the problem, but multiple solutions can be proposed, and therefore, the problem is approachable from different directions and by a large number of means;
- its parameters are variable and depend upon circumstances in the locality where deployment is planned or being carried out; and
- the roll-out undergoes the process of being controlled by various jurisdictions, and hence, the ultimate success of the roll-out depends on many vital but complex decisions.

The problem is difficult to solve because of:

- its complexity. It carries a variety of aspects and involves diverse processes. In consequence, a steep learning curve effectively impedes a comprehensive and thorough understanding of the problem. Even if an intention confines to a superficial grasp of the problem, the complexity still poses a challenging task, especially for a single researcher.
- its interdisciplinary nature. It concerns economic, political, social, regulatory aspects, etc. The number of aspects exacerbates the difficulty of cognition even further due to concepts, ideas, theories or methodologies rooted in distinct scientific disciplines, which makes the learning curve even more steeper. Because of that, an in-depth literature review should be also conducted throughout various research areas. Another difficulty derives from the fact that gathering a team of experts having diverse professional background is typically uneasy.
- harsh rural conditions that are being discussed in this thesis
- the research methods it entails. The kind of exploratory research is pertinent to a problem that is relatively unknown and unexplored, while it addresses new topics or research sub-problems. The difficulty lies in the fact that this type of methodology carries along with a risk of uncertain outcomes. Besides, high expertise is required to conclusively disprove the existing theories or explain why they cannot be employed in new circumstances. Similarly, a high level of proficiency is required to put forward and invent new concepts and methodologies. Apart from all of that, the measures of creative problem solving are perhaps essential beyond pure technical problem-solving skills.

- a number of problematic aspects it features. A separate section of the dissertation, i.e. section 1.5, was devoted to describing and explaining those aspects in details.

1.3.2 Research questions

The present work aims at getting a deeper insight into the economics of rural FTTH roll-out. The main research question involves a range of other enquiries, but it does not merely concern the problem of cost optimisation, i.e. the minimisation of Capital Expenditures (CAPEX) or Operating Expenditures (OPEX). Pure acquisition of the optimised cost does not provide us with the essential knowledge about the problem, and therefore, fundamental questions should be asked first as to how the rural FTTH deployment differs from the deployment in urban areas, and whether we should adopt the same strategies, or we perhaps should develop and control rural FTTH roll-out by some alternative means. The key differences between the scenarios embody:

- lower interest in FTTH service in rural communities compared to the urban case. Relatively lower demand has several sources, and the main cause allegedly results from high FTTH deployment cost. That expenditure is typically transferred and imposed onto end-users through service installation fees, which are prohibitively expensive most of the time; and
- an unpredictable expansion and growth of FTTH networks in rural areas. This can be linked to several circumstances, for instance, low foregone demand for FTTH service in rural areas. Another key factor, responsible for such uncertain growth, stems from unpredictable both timeline and locations where newcomers may potentially emerge.

Under those circumstances, we should formulate more pertinent research questions. Therefore, a preliminary enquiry should relate to potential means of making rural roll-out viable, and perfectly, a commercially viable case. In this context, a viable roll-out does not certainly indicate a cost-effective deployment but has miscellaneous connotations to:

- potential means by which the roll-out can be enabled or facilitated in such severe situations as that one involving low demand for FTTH service. The uptake of the service is expected to continue at low or very low rates in the foregone situation, from a long-term perspective;
- potential means of handling newcomers and sustaining the network growth seamlessly - or ideally - in a cost-effective way; and
- potential means by which FTTH deployment receives the aid of rural-oriented methodologies, strategies, approaches or techniques.

Eventually, an attempt is made to encapsulate a number of foregone research questions into a single and concise research question, i.e. the main research question of this thesis, which is: What are the frameworks or the means by which urban and rural FTTH roll-out problems can be both differentiated and understood. And as a result, the rural-oriented roll-out strategies worked out and pursued so as to enable and facilitate a viable rural FTTH roll-out, through sustaining a seamless network growth and development, ideally by accomplishing a cost-effective business case in the long run?

1.3.3 Hypotheses

Apart from the research question, the author of this thesis proposes the following hypotheses, which stem from the literature review and initial investigation into the rural roll-out problem. The hypotheses represent an attempt to explain the major barriers to overcome in rural roll-out problem. The author of the thesis supposes that:

- one of the fundamental obstacles results from the lack of adequate understanding of the problem and the lack of a holistic framework (both conceptual and analytical) intended for rural FTTH deployment. A holistic framework indicates that a problem is treated in the holistic way so that everything which can contribute to problem resolution is taken into account. Still, the thinking about the problem is contextual and depending on specific circumstances. For example, the obstacle to FTTH roll-out could be a non-technical cause, e.g. the lack of suitable regulations to use novel deployment techniques in the outside plant development;
- one of the most severe barriers originates from the fact that demand for FTTH service in rural communities is commonly difficult to predict. This factor renders telecom operators reluctant to roll-out most likely because of the threat of a risky investment emerges. The actual risk is associated with the uncertainty in the cost of deployment subjected to undefined network expansion plan and growth;
- deployment strategies designed for urban FTTH deployment may not suit rural roll-out, and novel strategies should be devised to fulfil the requirements posed by rural environments, and in particular they should cope with the uncertainty resulting from unknown demands for FTTH service in rural areas; and
- when a number of specific conditions hold in a particular locality and circumstances, FTTH roll-out can become commercially viable in a long-term perspective. For that purpose, the framework should also incorporate suitable economic tools such as business models, incentive schemes, etc.

1.3.4 Research methodology

The main purpose of this section is to propose and discuss the methodology that will be used to address above research questions and test out hypotheses. Furthermore, the assumptions are discussed and criteria used to evaluate our research.

Only an outline of the framework is provided at this stage, but the author of this thesis came up with a more elaborated research plan shortly after the literature review has been done. A separate Section 3 has been devoted for further elucidation.

1.3.4.1 Testing hypotheses

In order to understand or validate the hypotheses, different measures should be used. Some of hypotheses can undergo experimental testing by using real-world FTTH deployments carried out in different localities worldwide. This type of provision bears certain limitations. It is subjected to many specific conditions and circumstances present in a given locality, and most typically, it cannot be generalised. On the other hand, the same conditions prevailing in certain localities can be examined in different environments along with other essential conditions so as to extend the validity of hypotheses to a higher extent. Real-world deployments or trials are genuinely helpful in the process of assessing and preparing plans or strategies for deployment or roll-out. They offer a unique insight into the best practices of deployment in the outside plant, which is unlikely to be normally acquired by other means. In spite of the various benefits of real-world trials and deployments, the following limitations make them impractical for us to adopt. Foremost, the overall cost of deployment is perhaps preventive for universities and also certain decisions to be made remain beyond the jurisdiction of universities, and hence, the involvement of incumbent operators, policy regulators and other third parties is inevitable. Also, it might be overly expensive to test many different hypotheses solely in a real-world environment.

Therefore, the author of this thesis opts for a computer-aided network design methodology and attempts to develop the methodology so as to recreate a real-world scenario in our filed-like-trial simulator. More details was provided on the methodology and what else should be considered in the simulations later on in this section.

1.3.4.2 Assumptions

Nevertheless how accurately the simulation is intended to be run, it is likely to be carried out under certain assumptions. In this thesis, the source of the assumptions mostly relates to the scarcity of data sets for a real-world scenario. Requisite data is not available due to a variety of reasons. It is either not present in the public domain, or it requires additional work such as surveying to be collected. The main assumptions appear as follows:

- the exact time and location where demand for FTTH service is expected remain uncertain. In other words, end-users are free to join the network at randomly selected time intervals. We may still suppose that demands are higher in the locations nearer to the city centres or where larger clusters of end-users are formed. However, a survey or a dedicated study would be required to poll end-users about their expectations and actual interest in FTTH service; and

- the lack of requisite data is tried to be compensated by data extrapolation or interpolation. Otherwise, a relevant comment is left to justify, clarify or terminate further research.

1.3.4.3 Exploratory research and top-down approaches

The exploratory research strategy is what we have opted for, and we additionally prefer to employ a top-down approach with the intention of complementing the exploratory strategy. The top-down approach is suitable for exploratory research because it assumes beginning a study with a superficial examination rather than detailed so as to acquire general knowledge about the problem in the first place. This enables the opportunity of further planning toward more specific research areas and allows to decide which of the concepts should be explored more thoroughly. In such a way, the research efforts can be properly managed. The adaptation of the top-down approach results in the examination of LR-PON roll-out being considered in the following scopes:

- the global scope, which had been initially considered, but due to questionable quality of the global data set [16], it was omitted. The data set basically lacks precision, and by using it, we might perhaps fail in underpinning meaningful outcomes. Whereas it provides figures for the density of inhabitants per square kilometre, no data for householders per kilometre is contained in the data set. Such information concerning geographical coordinates of householders is essential to what we plan next in our techno-economic studies.
- a nation-wide FTTH deployment study to be carried out in Ireland – with the goal of differentiating between urban and rural circumstances and FTTH deployments
- a very rural areas or counties in Ireland - with the goal of delving into rural FTTH roll-out economics. Another goal is to examine urban-oriented deployment strategies in a different environment, i.e. rural environment.

1.3.4.4 Criteria used to evaluate the research

The investigation in this dissertation centres around the techno-economics of rural FTTH deployment. In order to describe and analyse our findings, the author of this thesis considers the following measurements, variables or criteria:

- Quantitative:
  - the amounts: fibre cables, access nodes, etc.
  - the number of PONs, i.e., the number of OLT cards
  - the total cost of deployment, i.e., provided that take-up rate is equal to 100%
  - the cost of deployment as a function of take-up rate

  - the cost associated with a specific stage of network development, up-front cost, startup cost, etc. Up-front cost can be defined as the cost required to provide everything necessary before end-users can order and start using a network and services provided over it. The startup cost can be described as the initial up-front cost. Up-front cost is associated with the infrastructure deployment and provision of resources for further network growth, i.e. further up-front costs can be imposed when the network expands. Up-front costs sum up to the total cost of network deployment which can be covered by end-user fees or other sources of funding.

- Qualitative:
  - sustainability – the (network) capability to sustain seamless growth
  - cost-effectiveness – whenever a quantitative assessment is unfeasible, a discussion should rather indicate the most promising alternatives, especially in the light of long-term roll-out
  - sharing. Resource sharing is one of the key concepts leading to the improvement of the economics of FTTH deployment.

1.3.4.5 Summary

The LR-PON examination in our case boils down to performing techno-economic analysis. This kind of analysis is intended to provide an overview of the economic efficiency of LR-PON technology in relation to a real-world FTTH deployment. The analytic part of the framework is to be based upon concepts rooted in the spatial data mining discipline with the clustering analysis picked as the central topic. The author of the thesis planned to examine various kinds of clustering algorithms so as to group householders into hierarchical clusters and layouts of end-users. Such sort of hierarchies can be then converted somehow into PON layouts ready to be deployed in the outside plant, thereby a road map to a real-world FTTH deployment emerges. The conceptual part of the framework is intended for highlighting the concepts pertinent to the rural roll-out, with special emphasis on both technical and non-technical rural-oriented techniques, approaches, strategies, incentives, creative problem-solving outcomes, etc.

1.3.5 The main research question and related specific questions

This section is devoted to summarise the deliberations presented above. The purpose of this section is to propose a single generic research question for the thesis and derive a number of more specific research questions pertaining to the main research question.

In this thesis, the main generic research question is: what are the cost-effective deployment strategies for the rural FTTH roll-out?

A number of more specific questions can be asked to this generic question, with accordance to the words that defines the main question, as follows:

- ”cost-effective” - What conditions make the deployment more cost-effective? Under which conditions the roll-out is commercially viable?
- ”deployment” - What technology or architecture should be employed for deployment? Which clustering algorithms to use and how to combine them?
- ”strategy” - What are the most important variables in the problem that change over a long period of time? How these variables affect the cost-effectiveness of deployment?
- ”roll-out” - How to make FTTH service in rural areas nation-wide?
- ”rural” - How this case differs from the deployment in the urban case? Should the deployment in the rural case be different than in the urban case?
- ”FTTH” - Why FTTH technology and not the other technology for the deployment in the rural case?

1.4 Motivation

The goal of this section is to explain the motivation that drives the author of this thesis towards the mitigation of the rural FTTH roll-out problem.

Rural FTTH roll-out problem offers all sorts of research opportunities. This creates the source of strong motivation to sort out the key of them so as to facilitate the research process for all researchers enthusiastic about the problem. Besides, the author’s motivation also relates to sorting out the research problem in terms of past professional activities including network design and optimisation. As earlier mentioned, the focus of this thesis concerns the access section of LR-PON and its optimal deployment. Designing an effective deployment strategy for the access part of LR-PON appears amongst the most challenging and in fact most urgent issues in the rural FTTH roll-out problem.

Moreover, the problem persists worldwide, and affects not only weak economies but also developed countries. Statistics in [17] indicate that apart from a few countries on the globe, FTTH household penetration rate is widely low. The rate is typically even lower in rural areas for a variety of reasons discussed throughout the course of this thesis.

The author of this thesis also firmly believes that rural FTTH roll-out is viable or commercially viable in a long time horizon. In effect, the roll-out should positively influence local both communities and economies, which should in turn contribute to the global economy. Also, there is a high motivation to more frequently consider fibre service as one of the essential basic commodities besides water or electricity. This consideration have came in view of high motivation to develop the information society. Nowadays, both the development of economy and the quality of life in society heavily depend upon the presence of advanced information technology and the capability of having rapid access to bandwidth-demanding services or applications. Due to the lack of high-speed Internet service in rural areas, supposedly only vain attempts can be made to create remote businesses , i.e., without video conferencing of superior quality and all other facilities that FTTH unlocks. Aside from that, FTTH serves for example e-medicine or educational needs. Under those circumstances, the relocation of people becomes less common, thus leading to lower travel expenses, CO_2 emission, and so forth.

The problem of unequal access to high-tech capital is broadly known as Digital Divide [18]. In fact, urban and rural communities typically have uneven chances to leverage the capital provided with the most advanced information and communication technologies (ICT). As a consequence of that, an unequal development of economies and societies describes a plausible scenario which may further lead to the reinforcement of developed regions and regression or depopulation of underdeveloped rural regions. The split in the society may also be anticipated to deepen in a long-term perspective. The issue has been addressed by the European Commission in Digital Agenda which has envisaged the provision of high bandwidth broadband access of 30 Mb/s to entire population in Europe by 2020 and 100 Mb/s to not less than 50 % of the population [19]. The author of this thesis has strong motivation, and aims to alleviate the problem in the country of Ireland and in fact worldwide.

Among all European countries, Ireland offers an ideal location for the examination of rural FTTH roll-out. As a country, it has an unique distribution of end-users, and a large portion of householders (i.e. single dwelling units) resides in rural or very rural areas. The rural communities are scattered around the whole country rather than concentrated in a few isolated locations. The distribution of dwellings in Irish rural areas is irregular and thus problematic in orchestrating the roll-out. It happens most likely due to the scarcity of official rules and regulations. Therefore, the author of the thesis has an increased motivation to capture the attention of policy-makers, telecommunication regulators, and so forth.

1.5 Key aspects of the problem - further exploration

The goal of this section is to identify the most essential topics for consideration in further studies aimed at the rural FTTH roll-out problem. This section is also devoted to serve other researchers working in different fields because their contributions coming from different directions are necessary to mitigate the kind of an interdisciplinary problem.

The purpose of this section is to explore deeper the key aspects of the problem so as to ease the understanding of the problem, facilitate further literature review, help to set potential research goals towards more specific research areas, and describe the problem with respect to the urban case.

1.5.1 Interdisciplinarity

As earlier mentioned in section concerning problem statement 1.3.1, the difficulty of the problem arises from the interdisciplinary nature. For that reason, the research activities should be carried out throughout various disciplines, and their focus should expand beyond strictly technical aspects. For instance, it might be the case that although having a new cutting-edge technology in place, some other barriers perhaps hinder the roll-out. Technology is in fact a common denominator linking different disciplines and aspects what can be exemplified as follows:

- economic:
  - suitable business models might enable commercially viable rural FTTH roll-out in a long-term perspective
  - new innovative models of economy involving FTTH networks and services as the foundation for the economic growth
  - suitable business models leading to the increased sharingness of resources, thereby reducing overall expenditures
- political:
  - all sorts of incentives encouraging end-users to take up FTTH service
  - the intervention of government towards local governments and rural regions
  - new legal regulations affecting the market of broadband services, e.g., establishing the minimum level of data rate offered to the public
- social:
  - surveying end-users about what are the limiting factors on the decision to take up FTTH service
  - uncaptured benefits of FTTH for rural communities
  - consequences of neglecting the development of FTTH networks in rural areas

1.5.2 Prohibitive or uncertain overall costs

The bar to enter the market for FTTH in the rural case is generally high. First of all, bringing FTTH to rural areas is typically associated with relatively extensive deployment cost unless a suitable infrastructure is supported ahead of FTTH deployment. Otherwise, the deployment of new infrastructure usually incurs extensive labour cost, in some cases accounting for up to 90% of total FTTH investment [20]. In most rural cases, a new infrastructure must be constructed from the ground up because old copper infrastructure offers virtually no support for new FTTH deployment. On the other hand, in the urban case, a system of underground ducts and manholes might serve spare capacity for FTTH deployment. The infrastructure is designated to accommodate the equipment such as fibre cables or enclosures with optical splitters. The infrastructure may also be used to provision spare capacity in view of anticipated network growth. Such increased cost of deployment does not solely result from the sparsity of end-users in rural areas but additionally from the irregular spatial distribution of them. The type of dwelling also has an effect on the overall cost of deployment, i.e., it is typically more costly to bring FTTx to a number of single-dwelling units when compared with a single but multi-dwelling unit. In both cases, the same number of householders is considered. Also, the overall operational cost is expected to be higher than in urban case due to the sparsity of end-users. The overall maintenance cost depends on many factors, e.g., on the kind of network deployment which can be either overhead or underground.

The cost of deployment varies in different countries or regions, depending on, e.g., soil type, climate or the involvement of government. Still, the labour cost appears as the major cost in the investment unless a more cost-effective technique is proposed and selected for deployment. The uncertainty in the overall cost stems from the circumstances that have already been described in problem statement section 1.3.1.

1.5.3 Scarcity of data sets

Nowadays, the process of FTTH planning is normally computer-aided, and digital data sets of various kinds are essential in the process of cost estimation of deployment or performing its optimisation. A problematic is a situation where demanded data set does not appear in the public domain or its quality is inferior. For example, consider the following public data set [21]: the data representing the network of streets has satisfactory quality, whereas the quality of the data describing the locations of householders is poor. It contains partial information specifically for the rural regions. Therefore, it might be problematic to carry out the examination of FTTH deployment at the national level. On the other hand, the examination is feasible for smaller regions with suitable data sets in place. A fundamental issue arises from the lack of a single and consistent data set, which should be addressed before planning and optimisation of deployment can be both started.

A pricing scheme defines a crucial data set to the whole design of FTTH deployment. Such scheme encompasses a variety of selling prices for the components of FTTH network, whereby distinct FTTH deployment strategies can be devised. In order to devise a cost-effective strategy, a pricing scheme should be prepared in such a way as to suit the deployment in rural areas, e.g., it should involve a cost-effective deployment technique. The process of preparing a pricing scheme gets complicated by the fact that plenty of vendors and components is present. Moreover, prices are variable. It is also problematic to obtain useful data concerning pricing scheme from the private domain. Also, the value of price depends on many circumstances such as the scale of deployment. Furthermore, the prices for novel technologies that has not been yet commercialised are in fact unknown, e.g., as exemplified in a study on a novel technology deliberately designed for rural FTTH deployment.

1.5.4 Problematic expansion of the network

Sustaining a seamless FTTH network growth in a cost-effective way, without causing a disruption to the network operation and end-users, is presumably far more challenging in the case of rural environment. The problem is deeply rooted in sparsity of rural populations, and also, in unpredictability of both end-user demands and network growth, as already detailed in problem statement section 1.3.1.

Many other reasons increases the difficulty, i.e., the lack of suitable data sets, the lack of legal regulations. For instance, to ease the planning and development of FTTH networks in rural areas, a data set could be created that is confined to the most probable locations for where new dwellings can appear in the future.

1.5.5 Lack of suitable technology

Behind the absence of satisfactory technology may lie the following:

- basically, the lack of cost-effective technology. That problem also has many root causes;
- adequate cost-effectiveness of technology enabling mass market production;
- other barriers such as legal regulations.

Furthermore, FTTH can be deployed in a great number of ways, and making a right selection of suitable technologies is also problematic. The goal of technology selection is not solely directed toward employing the state of the art set of technologies, but it is mainly about proposing a holistic approach that enables a cost-effective deployment in the long-term run.

Moreover, a decision-making process on whether research on a novel technology should be started must be typically preceded with another study, e.g., a techno-economic examination showing prospective gains and cost-effectiveness.

1.5.6 Lack of suitable deployment strategy or approach

Technology is all-important but merely a single factor amongst all of the factors determining the way FTTH deployment is to be carried out. A deployment strategy is devised so as to provide a viable or more cost-effective deployment. Such strategy should be devised toward the exploitation of technology in a long-term perspective, and by consideration of further factors that loosely pertain to technology. As already mentioned in problem statement section 1.3.1, a deployment strategy in rural case might need to adopt different approaches as opposed to the ones that are being employed in the urban case.

1.5.7 Difficult optimisation problem

In both urban and rural cases, the deployment of FTTH imposes a complex network design. Moreover, the optimisation of FTTH deployment is not trivial and can be classified as extremely large-scale optimisation problem. This is because the overall number of optimisation both variables and constraints is proportional to the planned total number of end-users, road segments, access points, and so forth. And in fact, this figure can grow extra large even for a relatively small rural area under examination. Therefore, the provision of optimal solution to the whole problem might be overly difficult and technically infeasible. A sub-optimal solution of a lower quality can be still be found through the employment of heuristic optimisation techniques or else combined over optimal solutions of several separate sub-problems.

On the other hand, the density of end-users in rural areas has relatively lower level compared with the urban case. As a result of that, the complexity of optimisation problem is also relatively lower. This fact can be exploited in dealing with the problem from a number of different perspectives. More resources can be devoted to improve, e.g., the granularity of certain data sets. For instance, a larger set, which has increased number of fibre access points, can be used in the evaluation of optimisation model. This in turn may lead to more cost-effective network design, and give more flexibility in sustaining network growth more seamlessly.

1.5.8 Unimplemented business models

The lack of suitable business models results in a delayed roll-out or its permanent standstill. Network operators or other parties that will bear the cost of FTTH deployment might in fact defer the decision on whether to roll-out FTTH in rural areas until economic conditions improve, e.g., until rural areas are more urbanised or until urban roll-out is essentially over.

A number of factors exacerbates the implementation of business models. For instance, an attempt to combine a number of deployments into a shared one might fail owing to the conflict of interest among various parties that could potentially set up a joint project. For example, a deployment of water supply system or any other supply system could be carried out alongside the deployment of fibre duct system.

Challenges in the scope of business modelling requires creativity, divergent or visionary thinking beyond contemporary economics or wide-spread opinions, which is also difficult to being addressed.

1.5.9 Neglected legislation initiatives

The lack or negligence of legal regulations might be a direct cause of both irregular and sparse end-users distribution in rural areas. For instance, UK has introduced constraints on building one-off housing, i.e., the building of new houses is demarcated to areas located nearby old buildings, so that the negative effect of end-users sparsity can be substantially mitigated.

Legal regulations present a strategically important case in the process of making a new technology authorised and allowed for public use. There might be a situation where more cost-effective technology cannot be employed just because inadequate legislation prevails.

Further legal regulation might be inevitable in supporting underfunded rural areas, and therefore, additional directives by government or local governments might be required. Although the delivery of legal acts is beyond the scope of this thesis, the author of this thesis stresses that without suitable policies, the roll-out might be delayed or consistently blocked.

1.5.10 Deficiency of drivers

The roll-out is driven by many factors which can be classified as either apparent or potential, i.e. unknown or hidden. A lot can be done to unlock the potential, and thereby enable additional driving forces. Amongst all potential candidates, the work on novel applications of FTTH such as e-medicine is worth noting and doing. In fact, the lack of so called ”killer” applications demanding utmost data rate or symmetric bandwidth definitely does not help turning end-users to FTTH.

Creativity, divergent or visionary thinking should be the tools to learning and in fact creating new needs that basically remain out of modern imagination. Unconventional ideas may have a big potential payoff, yet their root sources remain initially unknown or rare and thus hard to be discovered.

There is a number of potential use cases that could be successful in mitigating the remoteness or isolation of rural communities, in particular, these use cases which leverage the symmetric bandwidth of PON technology and could serve high bitrate services such as:

- hologram-based bi-directional conferencing;
- educational, remote learning or training (e-learning);
- e-medicine, e.g. remote testing (upstream streaming), remote surgery of animals;
- virtual reality or interactive gaming which involves high throughput and low latency;
- thin clients or backups for seamless remote working;
- remote monitoring of any kind that requires processing in data centres;
- virtual meetings, e.g. yoga, sightseeing, cottage showcase.

1.5.11 Inadequate or poor comprehension

Inadequate or poor comprehension of the rural FTTH roll-out problem (and its key aspects) has a number of negative consequences, and might lead to discontinuation of research, false conclusions or ineffective deployment of FTTH in rural environments.

1.5.12 Summary

The success of rural FTTH roll-out is variable depending on a multitude of factors. It relies on the overall ability to combine the efforts of researchers working in different disciplines and across various research fields, and, besides, the adequate involvement of governments, policy-makers, and telecommunications regulatory authorities. Furthermore, the conditions in the rural case involve distinct requirements compared with the urban case. Also, the rural deployment tends to cause more difficulties and challenges.

1.6 Publications

This section serves to highlight the publications, which resulted as the outcome of this thesis.

Journals:

C. Zukowski, A. Mukhopadhyay, D. Payne, and M. Ruffini, *"Cost analysis of rural roll-out using a long-reach passive optical network: trading off the upfront cost under uncertainty of the user take-up rate,"* Journal of Optical Communications and Networking 13, 69-84 (2021).

Conferences:

C. Zukowski, D. B. Payne and M. Ruffini, *"Optical splitters configuration for long-reach passive optical network deployment,"* Proceedings of the 2013 18th European Conference on Network and Optical Communications & 2013 8th Conference on Optical Cabling and Infrastructure (NOC-OC&I), Graz, 2013, pp. 185-190, doi: 10.1109/NOC-OCI.2013.6582888.

C. Zukowski, D. B. Payne and M. Ruffini, *"Modelling accurate planning of PON networks to reduce initial investment in rural areas,"* 2014 International Conference on Optical Network Design and Modeling, Stockholm, 2014, pp. 138-143.

Posters:

S. Pal, C. Zukowski, A. Nag, D. B. Payne and M. Ruffini, "Cable length minimisation in long-reach-PON planning for sparsely populated areas," 2014 International Conference on Optical Network Design and Modeling, Stockholm, 2014, pp. 234-239.

2 Literature review

The first important goal of this section is to review the state-of-the-art means of approaching the rural FTTH roll-out problem. Through a wide-ranging review, whose focus ranges from social sciences to strictly technical ones, the aim extends to serve not only researchers in different scientific disciplines, but additionally, the policy regulators, the government representatives, potential investors, etc. The second goal is to examine the progress and the status of FTTH roll-out in the world. The third goal of this section is to provide a summary on the findings resulting from the achievement of previous goals, with respect to the main topic of this thesis.

Other goals set in this section focus on reviewing the suitable outside plant technologies and suitable mathematical algorithms, which will both serve the research and development of cost-effective deployment strategies for the rural FTTH roll-out case. These goals are pursued in sections 2.2 and 2.3 below.

2.1 The state-of-the-art means and progress of the roll-out

The roll-out is typically planned with respect to specific local circumstances and typically in the scope of a national roll-out plan, i.e. a country or some local districts. The review was organised accordingly, and it discusses the progress of FTTH roll-out in rural areas in various locations in the world.

2.1.1 Australia

A number of publications concerning rural FTTH deployment was released for this country. It might be associated with the fact that the government of Australia included rural areas into the national broadband deployment plan and showed special interest towards this case.

2.1.1.1 Techno-economic study of broadband technologies in sparse rural area

The process of picking up the right broadband technology for rural roll-out is not straightforward. The work [3] that was conducted in rural Australian area attempted to compare the cost performance of various technologies, i.e. PON, DSL and wireless Worldwide Interoperability for Microwave Access

(WiMAX). The motivation for this study resulted from the lack of similar studies explaining the economics of broadband technologies in the rural environment provided that increased demand for higher data rate was anticipated in the future. The authors claimed that the main factor delaying the roll-out was associated with a high deployment cost in rural areas as compared with a relatively lower deployment cost in the urban case. This thesis identified and discussed additional problematic issues.

The main result of this study contained a general conclusion which presented PON technology as the lowest-cost solution in the rural area that was investigated. The work involved a superficial techno-economic investigation, and the lack of details concerning assumptions and the methodology for yielding the results is a drawback of the study. Therefore, little chance was left for making a correct assessment of this work.

The authors did not focus on explaining how to build the lowest-cost PON network but on showing how the PON is the lowest-cost amongst the broadband technologies that were studied. Presumably, the explanation on how to build FTTH network was not the critical goal of their study. As the key cost differentiator in the cost comparison of technologies appeared the total cost of remote nodes (the wireless base station, Digital Subscriber Line Access Multiplexer (DSLAM) equipment), as shown in Fig.3.(a). That is, higher data rate incurred higher cost, which can be explained for different technologies such as:

- DSL - the reach of 2 kilometres was supported for 20 Mbit/s data rate, while for 50 Mbit/s data rate, a short reach of 300 meters was supported. The second variant involved a higher number of remote nodes (and OLT cards), thus a higher cost. This variant was necessary when a higher data rate was demanded by end-users;

- wireless - three households were served by a base station providing 20 Mbit/s data rate, whereas only one household was served by a base station providing a higher, i.e., 50 Mbit/s data rate. The reach was equal in both cases, so the cost difference was roughly three times,

while PON technology did not get affected by any kind of costly remote node in the outside plant. As a result of that, PON technology was presented as the lowest-cost technology meeting the requirement of higher bandwidth, in the sparsely populated rural Australian area.

The exception occurred for wireless WiMAX technology provided that the theoretical population density remained below one end-user per square kilometre. WiMAX outperformed PON technology but only in the case of the WiMAX slower variant (i.e. 20 Mbit/s). This presumably happened because the cost of remote nodes (i.e. costly WiMAX base stations) was compensated with no need for costly ”last mile” trenching. An investigation targeting comparison of broadband technologies to select the most cost-effective technology should also take into account the operational cost (e.g. electric energy consumption). That work did not consider that assumption. There might be a case showing that PON outperforms, for example, WiMAX in all of the mentioned cases.

The study involved TV service as a high-bandwidth demanding application, i.e. 2 channels of simultaneously watched broadcast TV and 1 channel for video-on-demand TV, which summed up to 18 Mbit/s. On-line gaming increased the total to 20 Mbit/s, which represented the minimum bandwidth requirement for a single householder. The comparison was made to compare technologies such as PON, DSL or WiMAX. The most viable technology assured the lowest CAPEX for deployment in view of increased demand for data rate up to 50 Mbit/s. No continuation of that work was proposed, which could conduct comparison for higher data rates and different technologies.

In fact, that study stemmed from another study [22] that also came to the same conclusion about cost-effectiveness of PON technology in rural areas. The second study is recommended for reading purpose because it contains a more concise description of the work done.

2.1.1.2 Novel PON architectures and relevant cost savings

The study previously discussed, i.e. [3], examined groups of remote rural end-users that were situated in a long distance to Central Office; far beyond the reach of standard GPON. The standard reach was 20-30 kilometres depending on what split rate was used. Another study [23] that was conducted by the same author attempted to improve the reach of standard GPON technology by adding an optical amplifier to GPON architecture. As a result of that, the standard GPON could operate with a capability of extended reach. An amplifier was employed to increase the power budget of the optical signal and thus extended the reach of PON to 60 kilometres. In order to keep the deployment more cost-effective, the active equipment (i.e. amplifier) was deliberately placed at Central Office. The study provided a preliminary experimental study to more advanced long-reach PON architectures such as DISCUS [24] architecture or more detailed studies on FTTH deployment in sparsely populated areas. The study [23] reported that one percent of the population in the rural area could not be reached. This situation occurred because the reach of 60 kilometres did not suffice. Therefore, a more advanced long-reach PON architecture might be required, e.g. an architecture proposed in DISCUS project. However, this study [23] did not address the problem of protecting end-users against fibre network failures.

The work [12], which is the follow-up of the study [23], stepped forward and proposed another improvement to the prior long-reach PON architecture. By using Semiconductor Optical Amplifier (SOA), one of Raman pumps could be eliminated. The results of another study [25] stressed that having two high power Raman pumps in a system was a shortcoming. A related study [26] proposed Erbium-Doped Fibre Amplifier (EDFA) long-reach PON architecture, and it claimed that the solution was cost-competitive compared with the system that was based on Raman pumps. Still, the study [26] did not provide numerical results for a fair comparison between EDFA (inexpensive, according to the authors) and Raman systems. EDFA system used a pair of fibres, which makes the cost comparison problematic. Two fibres to a single end-user might represent a cost-inefficient case, especially in sparse rural areas. The study [26] explained another way of increasing the reach of PON, i.e., the employment of smaller optical splitters.

The main savings that came from the employment of a longer-reach PON architecture in Australian rural areas were perceived in the reduction of the total number of local exchanges [12]. The following costs could be eliminated: operational real estate or renting a building cost, equipment (e.g. racks) cost, installation cost, electric supply and maintenance costs. The savings indicated the reduction of roughly 3.5 times in the total number of local exchanges in rural Tasmania. However, the problem of scarce fibre resources was expected to occur in a real-world deployment in Tasmania. Additional civil work was expected so as to deploy additional fibre cables (e.g. into the ducts) for long-reach PON deployment to succeed. In the most extreme case, it could be even impractical to deploy entire long-reach PON network without additional civil work. Civil work is typically costly (e.g. trenching). The authors of that work proposed to leverage the resources of backhaul fibre (i.e. dark fibre) network. The study did not explain how to build FTTH network in rural areas, and it omitted to present the numerical results. Also, there was no follow-up study for that work.

2.1.1.3 Clustering methodology and economic threshold

The foregoing study [3] devised a superficial techno-economic model describing the economics of PON in rural areas. Another study [27] proposed and examined a more advanced model that involved a clustering algorithm and a real-world road map. The clustering tended to discover the areas in which PON deployment was potentially economical, so that the entire national broadband deployment plan could be optimised in that way. Clustering yielded a partitioning of end-users into clusters which were planned to either be covered with fibre or not. The decision was depending on whether a hypothetical cost estimated for a cluster exceeded a threshold. The value of threshold depended on the political or market-driven factors. That work raises the motivation for further optimisation, e.g., seeking the most promising positions for optical splitters or the most suitable routes for fibre cables.

The clustering uses k-means related algorithm as it minimises the squared error, i.e., the distance between houses labelled to be in a cluster and a house designated as the cluster centre. This type of clustering is not the most suitable choice for cost optimisation as it is further explained in Chapter 6 where k-median was proposed and used instead.

2.1.2 Denmark

In 2009, Denmark demonstrated a steady nationwide expansion of FTTH service also in rural areas [28]. Danish business model was the key enabler of the roll-out. The business model involved utility companies which were initially responsible for the supply of electricity. In fact, as a result of governmental regulations and power supply market liberalisation, the companies accumulated significant assets by selling off electricity production shares. After that, the companies confined their responsibilities to the distribution of electricity. The assets that were earned could be next spent on building new infrastructure serving FTTH roll-out. The companies implemented the idea of “Electricity-To-All” for FTTH, i.e. most of utility companies decided to implement and followed “Fiber-To-All” policy. Therefore, consumers situated in both urban and rural areas could equally profit from FTTH service. The service in rural areas was provided in spite of expected long pay-back time or ultimately inviable investment. The main principle of business model implied that the companies were owned by consumers. This factor might further help in bringing FTTH service to everybody. Other countries may also make an attempt to follow “Fiber-To-All” policy.

The deployment of FTTH in Denmark was challenging. Danish deployment involved digging trenches for the purpose of underground infrastructure. Utility companies had to share the investment so as to reduce the overall cost of deployment: airborne power lines were dug down alongside the tubes for optical fibres. According to the authors of that work, the labour cost was estimated as the major cost of entire investment in rural areas, accounting for an approximate 80% - 90% of total investment. Why not to employ an alternative deployment approach that is more time and cost-effective? This could reduce the deployment start-up cost of FTTH and the involvement of costly labour.

Only 1% of all householders in Denmark in rural areas had no access to fixed-line broadband technologies (xDSL or fixed WiMAX) in 2009, whereas 3% of householders could demand the access to data rates higher than 144 kbps; the rest of country had access to 2 Mbps data rate and higher (downstream). A relatively small number of householders (1%) suffered from a lack of broadband access. Denmark decided to adopt a middle-mile solution towards FTTH, i.e. wireless WiMAX technology, so that any sort of broadband access was offered in remote rural areas.

The authors of that work explained that FTTH had positive effect on depopulation of rural areas, home working, remote education, or ICT aided farming. More economic opportunities for rural communities might be created. That study identified that insufficient research was conducted on the real impact of FTTH service on economy and society in rural areas. Cross-disciplinary research was proposed to provide numerical results and a meaningful assessment of that impact.

In 2009, Denmark had a plan to cover 60% of householders with access to fibre service in the following 4-6 years. Statistics [29] showed that fiber-to-the-premises (FTTP) coverage (% of homes) in mid-2018 attained in Denmark:

- 65% - total coverage,
- 60% - rural areas.

However, statistics also showed that the the real household penetration was about 15% of the entire population of householders in 2019 [17]. So, there was a high gap between total coverage (65%) and real household penetration (15%). It would be interesting to understand which factors hindered both urban and rural FTTH roll-out in Denmark.

The overall cost of the deployment was estimated in Denmark, but the spread was high, i.e. between 1.3-2 billion Euro. This might exhibit a lack of suitable planning tools. There was no follow-up study for [28]. The same authors suggested a copper-fibre infrastructure switch-over plan in their subsequent publication [30].

Denmark had a long-term goal to achieve 100% availability of FTTH in the most rural municipalities: Tonder, Varde, a part of Ringkobing-Skjern, before 2015. In order to analyse the progress, data was examined in sources [31] and [28]. The comparison shows how the availability of FTTH increased between 2008 and 2013. The availability of FTTH increased significantly, as illustrated in these data sources, i.e. up to 80% – 100% in the most rural municipalities (Tonder, Varde and part of Ringkobing-Skjern). There was no follow-up work for study [31], and the information concerning the coverage in 2019 or 2020 in the most rural municipalities in Denmark could not be found. The average FTTP coverage in rural Denmark in min-2018 was 60% as it was mentioned above. The author of this thesis could not, however, find statistics concerning household penetration for Danish rural areas, but only a cumulative household penetration was known [17].

The authors of study [28] performed a more in-depth analysis of Danish FTTH deployment in work [32], and they enumerated a number of factors that possibly delayed the FTTH deployment in rural areas. As the major obstruction, the absence of government in the process of rural development was mentioned, i.e. Denmark decided to pursue market-driven FTTH roll-out. Another contributing factor was a relatively low subscription rate in rural areas; in other words, low interest of customers in FTTH. Part of companies ultimately decided not to invest in the areas having no potential for economic growth. The authors also pointed out that the lack of "killer" applications led to a situation where customers using xDSL (or cable) technology might be not interested in FTTH. Nevertheless, FTTH might be the choice in rural areas where there is no competition (no cable operators), and xDSL might not be cost-effective for high data rates in sparse rural areas. The authors also recommended that the improvement of deployment coordination was required because a vast number of companies took part. This was meant for avoiding common mistakes and improving the efficiency of the entire deployment. Furthermore, the necessity for planning tools was stressed. In fact, a large number of fibre tubes was dug down, but a significant amount of them remained unused owning to unsuitable planning or documentation. Also, the need for planning to be carried out globally was indicated by the authors of that work, i.e., for the whole area preferred rather than for separated smaller regions. The authors of that work justified the lack of exact statistics concerning FTTH penetration, in particular in rural areas. The main difficulty occurred in the activity of collecting data from a large number of companies.

Summing up: despite high FTTH coverage both in urban and rural areas [29], in many Danish municipalities the real household penetration of FTTH was relatively low in 2019 and accounted for about 15% of all householders [17]. The author of this thesis could not find a study that identifies the exact reasons of such a stagnation or a study that identifies the obstacles that could be overcome to increase the household FTTH penetration in both rural and urban areas in Denmark.

2.1.3 Sweden

Sweden also brought FTTP (FTTB or FTTH) to rural communities. FTTP covered 10% of rural Sweden, whereas xDSL had the dominant 90% coverage in rural areas amongst wired broadband technologies in 2012 [33]. Similarly, as in the case of Denmark, it would be interesting to understand the obstacles that prevented the development of FTTP networks in rural Sweden. The total FTTH household penetration in 2019 in Sweden was equal to roughly 9%, and the total FTTB household penetration was approximately 34% [17].

Swedish FTTH roll-out was driven by municipalities and the government. The government was issuing suitable policies since early 1990 so as to provide physical infrastructure, i.e. a foundation for FTTH [34]. The Swedish business model involved the deployment of dark fibre in competitive areas, whereas the government offered subsidies in rural areas inhabited with three thousand or a lower number of residents. The government also aided “open access” fibre networking so that various companies could leverage a common physical infrastructure. The infrastructure was typically controlled by a single company before. Overall, it was meant for increasing the competitiveness and enabling the adoption of many new services so as to attract more consumers to FTTH service.

The regulation by government specified that dark fibre should be available within a small number of kilometres to premises. The deployment of the last section of fibre connection between a source of dark fibre and an inhabitant had to be funded by the inhabitant. Despite of incentives that government proposed, such as tax rebate compensating for up to roughly 525 Euro for the construction of fibre connection, FTTH coverage was low in 2012 in rural Sweden (10% according to [33]). A presumption was that the process of building the final section of FTTH connection was somehow problematic, and it would be interesting to find out the root causes of that problem.

Sweden, likewise in Ireland, was an ideal location to carry out research concerning rural FTTH deployment since 25% of Swedish population lived in sparsely populated countryside [34]. There was no extensive research concerning rural FTTH roll-out in Sweden. The publications were centred around socio-economic studies which provided motivation and explained the profits resulting from having FTTH in sparsely populated and remote access rural areas.

The low level of FTTH household penetration in Sweden was most likely associated with the lack of adequate business models. Therefore, the authors of study [35] proposed a business model that had a vision beyond the traditional schemes which were neglecting ”uncaptured value of FTTH”. The main reason for the low level of FTTH household penetration was, according to the authors, the resistance of customers to pay more for a higher connection speed that FTTH offers, yet the revenue coming from the subscriptions was not expected to offset the cost of the new deployment. This led to a conclusion that FTTH deployment was unviable. The new potential source of revenue was associated with ”uncaptured value of FTTH“, i.e. the FTTH service offering the orders of magnitude higher connection speed (compared with xDSL) and highly improved quality of service. As a result of that, that added-value of FTTH was expected to enable novel products and services, leading to increased revenue which could compensate for the cost of FTTH deployment. That study described a wide range of benefits to ICT and society resulting from FTTH services, similarly as in Danish rural FTTH roll-out [28]: the importance of remote working, e-learning, e-government, e-health, which all mitigate the difficulties of transportation and the relocation of people. The emission of carbon and traffic jams could be reduced as a result of that. The authors of this work emphasised that the presence of fibre in rural areas could attract more companies to running their businesses in the rural markets, and because of that, the increase in the number of companies in rural areas was also expected. Overall, this might help prevent the depopulation of rural areas and lessen the need for people migrations, while improving tax income and the cohesion of sparsely populated communities. A long-term return investment business model was anticipated as likely inevitable, according to the authors of this study. Therefore, actors, such as public administrators, the investment or pension funds, which could sustain a long-term investment should be invited and take part in the rural FTTH roll-out.

In a subsequent study, the authors of [35] attempted to quantify both economic and social outcomes in areas where FTTH networks operated for years [36]. The study proved a low but significant correlation. The first important correlation indicated a positive increase in the employment rate from 0% to 0.2% within 2.5 years period. An increase of population by 0.25% was observed in the areas within 353 meters radius from already fibre-connected premises within 3 years period. Both observations are crucial in the context of both depopulation of rural areas and unemployment in rural areas. Due to a gradual increase in the availability of FTTH in Sweden, the above indicators were expected to further improve, which was considered as a topic of follow-up study. Interestingly, the emergence of FTTH networks contributed to significant savings because of the presence of fibre-enabled competition in the Swedish telephony market. The savings accounted for 30% in Stockholm (fibre penetration was equal to roughly 60%), and they were proportional to the availability of fibre in the region. For instance, in Jonkoping having 25% fibre penetration, a cost reduction of 10%-15% was observed. Total expected savings were estimated to hundreds of millions of SEK (1 Euro = 10 SEK) in both rural and urban areas. Presumably, FTTH could bring relatively higher savings per customer in rural areas because it replaces electric-inefficient copper broadband networks which are even more inefficient in sparsely populated areas. A consecutive study [37] was limited to urban areas (Stockholm), yet it showed a considerable “socio-economical” return. The return was approximately three times higher than the investment in FTTH infrastructure exactly was. For the return accounted savings such as lowered prices of connecting or data transmission, increased employment, the revenue of the ”open-access“ network operators, and increased value of properties because tenants were willing to pay an additional rental charge when FTTH service was available. The study emphasised the important role of municipality that helped to enable the ”open-access“ fibre model in Stockholm. Moreover, this was done with bank loans and without the necessity to acquire taxes. The opposed situation was present in Copenhagen, a city with similar economic potential, yet where only a single incumbent operator benefited from the infrastructure. Possibly this situation caused the lack of competitiveness and a relatively lower penetration rate of multi-dwelling units in Copenhagen equal to 20%, while it was 90% in Stockholm due to the “open-access” fibre network model. The importance of “open-access” model was underlined in that work. Companies bypassed the cost of expensive physical infrastructure construction, and they could lease fibre resources offered with the freedom to arrange their own fibre network topology. As a result of that, Information Technology (IT) flourished in Stockholm.

Independent study by Ovum (mentioned in [34]) quantified an increase in the number of companies operating in rural town Hudiksvall after FTTH service was rolled out, i.e., the increase was observed from 6% to 14% in the period between 2004 and 2009.

One of the main reasons for bringing FTTH to rural areas, according to the work [4], was a high maintenance cost of copper networks. The cost of maintaining a copper network could be even higher when higher bandwidth is demanded. The demand was constantly driven by applications demanding high data rate and by the government. The high cost of network maintenance was associated with the presence of a relatively high number of active nodes (per customer). In fact, another work [38] (cited in [4]) proposed an idea of aggregating those active nodes into a lower number of nodes and the idea of employing the passive infrastructure everywhere else. This would help to minimise the total number of active nodes and thereby reduce the operational expenditures. The savings could be spent on making the penetration of FTTH service higher.

According to study [4], Swedish network operator tended to close inviable rural copper networks, i.e. in the case when the income was lower than the operational cost, by replacing them with FTTH networks. The deployment of FTTH in rural areas was costly, and the authors of that work conducted a techno-economic study to explain what criteria must be met so as to provide an economic FTTH deployment in a particular rural area in Sweden. The deployment of dark fibre was considered in rural areas. The price for rural dark fibre was up to 3 times higher than in urban areas. This price, i.e. the lease of dark fibre per month, laid the foundation to the techno-economic study. The value was constant, i.e. fixed by a national regulator [4]. In the area under investigation, 2000 customers resided, and they required approximately 700 kilometres the fibre network to become interconnected. A long-term return of investment period was considered, i.e. 40 years. The calculation involved an additional fee for the installation of ”last mile” connection (1500 Euro) per customer. By considering Net Present Value (NPV) generated by 2000 end-users over 40 years period, the cost of building one meter of fibre network should not exceed around 8 Euro on average. Otherwise, the investment was not viable in the perspective of 40 years. In conclusion, the authors of that work claimed that they were able to build the entire fibre network below the cost of 8 Euro per meter (on average). In other words, a viability of FTTH investment in one of the most rural areas of Sweden was demonstrated, considering a 40 years payback time period, connection fee and dark fibre lease. Presumably, the total investment cost already included the construction of the final part of connection, i.e. between end-user and the nearest splicing point, but it was not explicitly stated in this paper. The author of this thesis interviewed the authors of that work, and they claimed that the real cost of deployment was nearly equal to the theoretical estimations done in this paper. The authors of that work explained that the core blue layout of fibre (in Fig. 3) was only a suggestion of a real-world deployment so as to cover all end-users situated within maximally 1km radius from the core access network. There was no specific optimisation approach in that work described. The work did not provide details on how to build a network with an average cost of 8 Euro per meter in a real-world scenario.

That study, i.e. [4], created a starting point for more advanced techno-economic studies which can assess the viability of FTTH deployment in other rural areas and by considering different payback period. A superficial techno-economic model, i.e. involving a limited number of parameters, typically yields useful but average cost figures (as shown in [4]). Generally, such a techno-economic model can be fed with the data resulting from an optimisation framework to make techno-economic analysis even more realistic and reliable.

Comparing the with the studies conducted in Denmark, the study [4] conducted in Sweden recognised the importance of particular advances in technology for FTTH deployment. The study delved into the technical details of rural FTTH deployment. First of all, that study considered passing end-users with the drops having a maximum length of 1 kilometre. Secondly, the alternative techniques of deploying FTTH in rural areas were considered for the deployment of infrastructure, i.e.: a) hanging on poles, b) digging down the ground, c) using lakes. Thirdly, the fibre infrastructure was expected to operate within a period of 50 to 100 years. To reduce maintenance cost over that extensive period of time, the recommendation was to bury cables in the ground so as to avoid costly repairs. Danish case considered 40 years period of payback time. On the other hand, using poles for deployment was mentioned as the alternative to trenching which was costly in the Danish case as mentioned above. Solid and strong poles were recommended for that purpose. The reuse of prior infrastructure was pointed out as an enabler of further CAPEX reduction. Deploying upon the existing infrastructure represents the brown field deployment scenario and might require different deployment techniques compared with the green field deployment scenario.

The longer reach of fibre-based access technology enabled the consolidation of active nodes and thus the reduction in the maintenance cost of active nodes. The nodes, cabinets in FTTC network, were initially serving end-users through the copper-based network within 4-6 kilometres radius to end-users. The authors of that work proposed to employ fibre optic transceivers to extend the reach of access network up to 80-100 kilometres. A longer-reach passive optical network created an opportunity for aggregation of active nodes. A reduction in the number of active nodes was possible thus a reduction in the maintenance cost. The authors of that work did not provide numerical results about savings after a lower number of active nodes were operating in the network. It can be only assumed that entirely passive optical network in rural areas led to certain positive operational cost reduction as opposed to running the copper-based network [4].

On the other hand, the consolidation of active nodes imposed a potential problem of ownership of consolidated nodes and the active equipment in those nodes. If many operators are operating over the same physical passive optical infrastructure, a fair way of accessing the active equipment has to be worked out. In addition, a business model should specify who is responsible and to what degree for the management of equipment.

Similarly to Danish case, Swedish FTTH deployment was market-driven. In order to increase the competitiveness in the market of fibre operators, the incumbent operator unbundled local loops so that other operators could leverage the physical infrastructure of access fibre networks and start providing various services to end-users. Moreover, national regulator fixed the prices of fibre leasing in the access network (both in rural and urban areas) thus making it easier for everyone to calculate the realistic cost of bringing and maintaining FTTH networks both in rural and urban areas.

The authors of study [4] stressed the requirement for fast but also symmetric broadband connections needed to satisfy further demands and to address the digital divide problem that appeared in rural areas. FTTH was indeed seen as a perfect candidate capable of offering both fast speed and symmetric broadband connections to rural communities. Furthermore, since a vast number of network components were designed to support Gigabit data rate, building a fast, i.e. Gigabit, FTTH networks should become cheaper due to a gradual drop in the price of components.

Similarly as in Danish case, work [4] indicated a high civil cost of FTTH deployment accounting for 60-80% of the total cost of deployment. That study briefly described a couple of technological advances that could help reduce the deployment cost. Recommendation encompassed: a) various trenching techniques, b) a deployment over electric poles, c) miniaturised multi-fibre cables, i.e. high density cables, d) using reservoirs (e.g. lakes) and specialised cabling systems designed for different purposes.

2.1.4 Finland

Finland was a unique country because citizens could demand a particular quality of broadband service. This was a result of legal regulations. In 2010, everyone could request access to at least 1 Mbps connection. This minimum speed was raised to 100 Mbps and planned to be provided to everyone by 2015 in 2013 [34].

2.1.5 Norway

Norway is a sparsely populated country which had FTTH household penetration at 35% in 2019 [17]. The author of this thesis could not identify studies concerning rural FTTH deployment in this country. However, a few studies referred to Norwegian FTTH rural roll-out.

Norway followed Sweden and adopted the "open-access" model. Moreover, small FTTH municipal networks were consolidated, thereby opening a wide market to service-rich providers [34]. In order to facilitate FTTH take-up rate, Norwegian telecom operator Lyse Tele dropped the price of installation fee dramatically. This action was similar to the Swedish tax rebate for the deduction of the final fibre connection construction [39]. Social aspect was pointed as of crucial importance: “nothing angers a Norwegian more than having some faceless corporation tunnel through his flower garden” [39].

In 2013 [40], Norway pointed out the lack of adequate and nation-wide regulations concerning digging the trenches. Every municipality established trenching rules independently, which had a negative effect on burying new fibre in the ground, especially in sparsely populated areas. It was claimed that this situation led to a deepening “digital divide” between Norwegian cities and rural areas. More importantly, the source [40] indicated the need for new regulation regarding micro-trenching technique [41]. This technique could significantly reduce the cost (and time) of laying down fibres into the surface of roads. Another important regulation, adopted not only in Norway, specified that any new multi-dwelling building must be developed with the internal FTTH infrastructure in place.

2.1.6 Ireland

This country is a highly suitable use case, because about 30%-35% of householders in Ireland reside in rural areas [42], but only about 2% of the total was served by FTTH by mid-2018 [43]. The number of FTTH subscribers rose to 12% in September 2020 [44], which is associated with the implementation of the National Broadband Plan, intervention of the government and the aid of the state [45].

2.1.7 Other localities

This thesis does not examine all the scenarios worldwide. The primary focus is on the most sparse (i.e. rural) European countries such as Denmark, Norway, Sweden or Ireland. Australia was also included since wide-ranging work on rural roll-out was done there. Other cases might be still worth studying.

Countries that featured a high household penetration might be worthy of further examination [17]. They may demonstrate an experimental proof showing that FTTH roll-out in rural areas could be indeed successful. Amongst the world leaders in the ranking of household penetration were situated South Korea or Uruguay in 2019 [17]. In those countries, FTTH roll-out was stimulated by the government. South Korea decided that the rural broadband plan had to be coordinated and facilitated by the government [46], which was expected to have a positive impact on the private sector. Study [46] identified digital divide problem resulting from the lack of fast broadband connections in Korean fishing and farming villages, i.e. the opportunities to access the same services such as Internet Protocol television (IPTV) or Voice over Internet Protocol (VoIP) were unequal for rural and urban communities.

The rural areas were not considered by private investors who typically rely on short-term return on investment strategy. Therefore, rural areas were classified as those that must be supplied by the government. The rural broadband in Korea involved the speed in excess of 50 Mbps, and long-distance reach were also supported. For remote access locations such as islands, wireless technology was preferred instead of wired technologies. Similarly as in many other countries, the emergence of FTTH was perceived in Korea as the enabler of innovation, i.e., a platform for numerous services developing on top of fibre networks. The study [46] enumerated various benefits that fibre networks enable. Korea had different business model because funding for rural areas was divided into 25%, 25% and 50% shares between government, local government, and a carrier in the private sector [47]. The construction work by the carriers was coordinated according to governmental policies so as to eliminate the duplication of work. Government stimulated the carriers by advantageous regulations regarding construction work. A follow-up paper [48] of that work analysed the status of ICT infrastructure in rural areas in 2013 and proposed governmental policies that might further accelerate the roll-out. The following obstacle in rural FTTH roll-out prevailed. The fact that private investors were reluctant to deploy in a less beneficial rural case. Therefore, the government had to provide financial support, specifically in the cases of covering villages inhabited with less than 50 householders. Korea created a new council, i.e. council of autonomous governments. The main purpose of that council was to encourage autonomous local governments and private operators to build FTTH networks. A valuable part of [48] was devoted to enumerate (in Table.2) a number of pilot services designed to serve rural areas: 1) low bandwidth rate services such as snowfall facility monitoring, 2) high bandwidth rate services such as remote health care service. The act of cooperation between different parties in the process of FTTH deployment was highlighted as the essential contributing factor to the success of FTTH deployment.

A study in Slovenia concluded that no broadband access network deployment was viable in rural areas due to negative NPV [49]. Therefore, the involvement of third parties was recommended as inevitable. The results were biased toward costly digging, and no alternative deployment techniques were proposed. A short period of the return on investment was considered, i.e. 10 years, and presumably, the installation fee was omitted. This is opposed to the assumptions in the study that claimed the viability of rural FTTH deployment for a long payback period of time and when installation fee was obligatory [4]. A misconception in [49] perhaps occurred because in the long-term comparison of FTTH and xDSL technologies, the operational cost (e.g. energy consumption) and maintenance cost were not taken into consideration. Another drawback appeared because the data rate parameter was ignored in the decisive cost figures. This led to a conclusion that depreciated the value of FTTH compared with many other xDSL technologies. The conclusion was opposite to the conclusion in [3]. There might be an issue with the pricing scheme in [49], i.e. xDSL equipment might be underpriced and the price of digging might be overpriced (compare with the price values in [3]).

Next, the section includes studies that do not pertain to any specific locality. The studies have therefore a universal value.

The study [50] attempted to analyse the economic outcome of co-investment, i.e. sharing FTTH/PON infrastructure among a number of operators. That work encompassed a number of important deployment-related aspects and topics: cost per home passed versus cost per home connected, FTTH unbundling, density geo-types, techno-economic modelling, the competitiveness among operators. That work compared four different PON architectures: GPON, XG-PON, Time and Wavelength Division Multiplexed

PON (TWDM-PON) and AWG-based Wavelength Division Multiplexed PON (WDM-PON). Various features of technologies were described to explain what affects the final economics of both deployment and sharing of FTTH/PON network. After the work was published, both GPON and XG-PON were commercially available, and TWDM-PON and AWG-based WDM-PON were expected to have commercial realisations (between 2016 and 2018). The comparison distinguished different geo-types, i.e. urban, suburban, and rural. The geo-types were distinct because parameters were different, such as: a) the length of feeder segment, b) the length of distribution segment, c) the unit cost of digging and the cost of preparing the trenches. The authors of that work considered approximate values for parameters that "do not correspond to any particular fibre deployment in Europe, and should be considered as values that are in the order of magnitude of fibre deployments that can be found in a few European countries". The study considered superficial and simplified outside plant PON topology, i.e. a single-stage of passive devices in PON deployment in the field (Fig.1. in that paper). The conclusion in that paper was interesting, and it described the economics of sharing FTTH/PON network among third-party operators and the main incumbent operator. The work relied upon such input data and constraints that might cause biased conclusion. The author of this thesis recommends using real-world data sets.

The study [51] discussed a number of factors affecting municipal strategies for broadband deployment. Municipalities played an important role in FTTH deployment, e.g. in Sweden. The investigation revealed that municipal initiatives strongly depended on nation-wide circumstances, and the initiatives of municipalities were different within the scope of a single country. The important role of governmental decisions on accelerating fast broadband roll-out was indicated. This work referred to other publications that targeted broadband roll-out in rural areas, i.e.: a) the impact of Public-Private Partnership model onto the broadband roll-out, b) the public policies that boosted the development of ICT sector in rural areas of Scotland. The sources of retrieving the funding was suggested as the main differentiator that determine municipal strategies which depend on: a) the contribution of public utilities (e.g. water or electricity companies), b) the partnership of private investors, c) right EU or national regulations that enable funding coordination within a relevant public framework, d) the subscription rate of customers, i.e. the percentage of customers interested in advanced broadband services (e.g. FTTH). This work discussed how various municipalities in Europe addressed and facilitated the broadband (e.g. FTTH) roll-out. There were many important topics addressed in this work. For example, Swedish and French governments funded the deployment of new national back-haul networks and incumbent networks. This established a foundation for municipal networks and their growth. Opportunities to adopt the all-optical network paradigm improved. There were two types of the business model mentioned that determined the final network architecture, i.e. retail or wholesale. Municipalities that were using wholesale model typically employed point-to-point architectures, whereas municipalities using retail model typically opted for point-to-multipoint network architecture. Point-to-multipoint architecture disabled the options of end-to-end dark fibre and fibre unbundling, but it lowered the deployment cost and offered Layer 2 open access products. As mentioned above, there might be different sources of funding which lead to the acceleration of municipal broadband initiatives. France successfully retrieved EU funding. The proposal had to comply with the rules: a) open market practices, b) proposal targets the least commercially viable regions (rural regions), but 100% coverage of the region must be guaranteed.

2.1.8 Summary and conclusion

The issue of rural area coverage remains widely open. In fact, in Europe, FTTP coverage in rural areas was below 20% (of homes) as reported in [43] in 2019. Moreover, the penetration seems low. Although the reports concerning household penetration rate are not publicly available for rural areas, it can be concluded for some countries, e.g. for Ireland, that the penetration rate in rural areas is below 3%. The problem of rural FTTH roll-out can be summarised as a real one and widespread, and that it still needs to be addressed.

The state-of-the-art methodology is complex, and a variety of methods has been developed to approach the rural FTTH roll-out problem. Overall, their applications showed to have positive effect on the roll-out, and some of them have been presented as key enablers: the involvement of local governments, suitable policy regulations, business models, and so forth. It is common that their implementation vary depending on the locality.

The methods concerning the economics of rural FTTH roll-out are specifically important to this thesis. Pioneering work in Australia and Sweden helped to answer some of our research questions. The state of the art advanced PON to long-reach PON and showed its benefits in the rural scenario. Through techno-economic studies, PON was indicated as the most cost-effective choice in a sparsely populated rural area, and FTTH as a commercially viable case in long-time perspective in very sparsely populated rural areas. These studies are very important, but they are incomplete in a broader picture. They neglect the description on how to deploy and leverage PON and other technologies to meet the requirements proposed in the techno-economic studies. Besides, these studies do not describe how to strategically deploy the network in a long term perspective, and they assume 100% penetration rate. The lack of adequate planning or planning tools is also reported in other studies.

To recap, the state-of-the-art FTTH planning and deployment methodologies could be further advanced in terms of rural FTTH roll-out.

2.2 Suitable technologies

This section delves into relevant details of technologies suitable for rural FTTH roll-out. Advances in technology enable further savings in the scope of network deployment and network operation. Therefore, this section reviews existing and researched technologies so as to identify the most promising and effective technologies serving the rural FTTH roll-out. Reviewed FTTH design criteria should not be limited, but they must include:

- long reach – both optical signal reach and the reach of fibre systems designed for the deployment in the outside plant;
- pay as you grow approach – this is required because the subscription rate of customers might be uncertain or low, and different parts of the network may be required to sustain different demands;
- seamless growth of the network – new houses may appear randomly in rural areas, sometimes in larger groups. Therefore, network design must provide flexibility so as to network structure can be seamlessly changed to absorb new customers;
- seamless migration to next-generation technologies – relevant for both rural and urban cases. Relevant constraints have to be taken into account in advance so old networks can undergo seamless migration to more advanced technologies;
- locality dependent constraints – governmental policies, severe climate, aesthetic effect of network design, etc.

The number of publications on FTTH technological advances is extensive. The following sources offer further reading:

- IWCS – International Cable & Connectivity Symposium [52] - contains a wide range of publications concerning FTTH outside plant deployment systems, and the systems designed to serve rural FTTH deployment.

2.2.1 Cable and duct systems

Fibre cable is a fundamental element in the design of PON networks. It supports the transmission of information over long links, i.e. several tens of kilometres, without the need of power optical signal regeneration. Fibre cables can be deployed in the field in many ways that are explained below. Using ducts appears as one of the most promising techniques for fibre cable deployment. Additional spare capacity can be provisioned in ducts during initial installation of ducts so that additional cables can be installed on demand. Cable burying technique might imply over-provisioning which may be overly costly approach in the rural case.

This can occur because demands in rural areas are usually difficult to predict, and network growth can either be addressed by 1) reserving, from day one, larger capacity, above current expected requirements or 2) employing an on-demand approach. The first approach, can become uneconomic for sparse populations, depending on the amount of over-provisioning considered.

The design of optical cables is not a topic of this thesis, and it was a target of [52]. The focus in this thesis is on particular design properties that enable the following feature:

- pay as you grow deployment – fibre resources can be easily accessed or provisioned in the telecommunication infrastructure that already exists. This ensures the scalability of network, i.e., network is robust against the arrival of new customers. For example, FTTH system demonstrated in the study [53] adapted a kind of blown micro cable to ease the installation of new fibre resources in the aerial network of ducts;

- long-reach installation – end-users are sparsely distributed in rural areas and therefore long-reach cable installation systems might be vital so as to reach small groups of customers. In urban areas, a short reach (e.g. average 70 metres in the UK) capability is typically required to connect end-users to a drop point. In rural areas, kilometres might be needed for the same purpose. For example, the study [54] investigated the performance of Enhanced Performance Fibre Units (EPFUs). The units were enhanced so as to reduce in-between duct and cable friction during the cable blowing activity; hence, longer cable blowing reach could be achieved. The study [54] demonstrated that this kind of cable could be blown up to 1 kilometre for particular combination of duct and cable. The resulting rate of blowing was demonstrated to be: a) roughly 15 minutes for one kilometre blow, b) constant. Those facts can be used in the process of preparing a cost model. Small-size cables (up to 12-fibres) shown in work [54] could be utilised for drops and within the drop section of FTTH network. Larger cables (e.g. 24-fibre and larger) due to more robust design of cable (and therefore higher cost) could be jetted for a longer distance, even up to 3.6 kilometres but typically with the help of lubricants [55]. The example shown in the study [56] employed different cabling types in different sections of FTTH. Higher robustness of infrastructure was required in sections beyond the drop section to protect a higher number of end-users. This was intended to reduce the chance of network failure and should in result positively affect the maintenance cost;

- aesthetic effect improvement – overhead duct or cable systems can help reduce the cost of deployment significantly, yet the visual impact of the overhead installation may present a problem to customers [53]. To mitigate the problem, the minimisation of cables was proposed to make them less visible. As a negative effect of minimisation, difficulties in accessing and managing multi-fibre cables occurred. This creates research questions as to whether the design of fibre access boxes and enclosures could be enhanced;

- dielectric cables offering a long span – telegraphic poles can be used for optical cable installation to reduce the cost of deployment. The installation typically occurs alongside electric cables, and therefore fibre cables must remain dielectric [57] to meet safety concerns. Moreover, such cables must support long span between a pair of poles up to a few hundreds of metres;

- reduction of installation time and reduced cost of materials – installation time can be decreased in a number of ways. For example, a pre-terminated fibre cable design was proposed and employed during the home visit and in the process of installing the drop cable [53]. In such a case, the splicing of fibre was not needed at the site of end-user, and other tasks were eliminated. The cost of material can be reduced in many ways. Researches who worked on cable design tended to minimise the size of cable and increase the density of fibres in cable [4]. It is recommended to use multi-fibre cables whenever it pays off. The idea of aggregating small cables into a larger cable pays off because the total price for a single large cable is lower than for a few smaller cables;

- specialised cabling system – in the rural case, e.g., water areas can be utilised for cable deployment, and therefore, a special type of cabling was employed [4].

An interesting cable system was demonstrated in Japan. The system was designed to decrease both installation time and cost [58]. The mid-span access technique offered access to individual fibres without a cut being made to other fibres in the cable. Such a solution could incur overprovisioning in sparsely populated areas. The mid-span cabling system could be used to serve randomly appearing customers. When an unplanned customer appears in a network, a new drop cable can be branched off from a mid-span access cable without making any disruption to the network operation. This created an alternative to blown fibre systems. Further research could compare both technologies and assess the trade-offs of deploying and using both of them. An advantage of the mid-span access approach is that the number of splices can be minimised because there is no cut being made to other fibres in the cable; thus the network quality improves.

The design of ducting systems is beyond the scope of this thesis, and the main focus is on the characteristics of duct systems that contribute to the cost-effective rural FTTH deployment. Using a duct system in rural deployment can be definitely recommended due to a number of advantages:

- lowered up-front cost of installation – study [59] (in Fig.1.) demonstrated a duct system that involved a single large protective duct that could accommodate a bundle of sub-ducts. More sub-ducts could be added on demand as the network grew. This feature is vital to rural FTTH roll-out whose overall progression is typically unpredictable, and additional fibre resources might be demanded almost everywhere in the network;
- modular deployment – contributes to a seamless network growth, i.e. it eases adding new sub-ducts, cables, enclosures, etc;
- convenient methods for branching off ducts on demand;
- additional protection offered to fibre cables – this is essential in the environments and for technologies such as aerial duct systems that are exposed to harsh weather conditions or situations where digging is planned nearby buried down fibre resources;
- rapid cable failure recovery – by having that, the removal of damaged fibre cable from a duct can be shortly followed by a new cable installation;
- improved aesthetic effect – a single duct groups a number of cables that would otherwise be hanging loosely or messily. This feature is of special importance in the design of aerial deployments;

- long lifetime of ducts – this allows costly replacement of ducts to be done less frequently. As a result of that, only old fibre cables that typically have a shorter lifetime must be swapped with brand-new cables.

A demonstration of an aerial ducting system designed for remote access (rural) areas, e.g. rocky mountains, was shown in work [53]. Another study [60] compared different FTTH deployment systems designed for the same purpose of providing a fibre connection to Single Family Units (SFUs). This type of dwelling unit typically dominates in rural areas. The results showed that air-blown fibre deployment system outperformed traditional solutions in terms of the deployment cost. Significant factors turned out to be the labour cost and the fact that each system involved distinct equipment in the distribution section of FTTH network.

2.2.2 Passive decouplers and their housing equipment

Passive decouplers enable the decoupling of optical signal without the need of optic-electric-optic conversion of the signal. Basically, passive decouplers are employed to interconnect fibre cables in a point-to-multipoint fibre network topology. Passive decouplers main responsibilities include:

- splitting the power of an optical signal coming into an input port of a passive device. Many equally powered signals leave the device through respective output ports. This kind of passive device is known as an optical (power) splitter. The power is typically distributed equally across output ports. However, there was also a power splitter invented that is able to split power unequally;
- decoupling multiple wavelengths coming into an input port of a passive device. A number of separated wavelengths leave the device through respective output ports. This kind of passive device is known as an array waveguide grating (AWG).

From the perspective of cost optimisation, optical decouplers are essential in the process of lowering the deployment cost. They improve the sharing of the physical infrastructure hence leading to a lowered amount of fibre resources required in FTTH deployment.

Power optical splitter has some characteristics that are crucial to the optimised FTTH network design. First of all, different size splitters can be applied depending on the density of end-users clusters in rural areas. A splitter can be equipped with an additional input port. This increases the cost of splitter but enables a non-disruptive network troubleshooting. As mentioned above, equal power splitters or variable power splitters [61] could be employed in FTTH deployment. The equal power splitting is, in fact, a common option. By using unequal power splitters, the deployment cost could be further reduced. For example, unequal power splitters could be arranged in a chain of, e.g., 1x2 optical splitters featuring high 20:80 power split rate. Such cascade could be formed at the "last mile" of FTTH network, i.e. between a drop point and a group of end-users located along the road. Such an approach could be combined with the mid-span fibre access approach that was mentioned above. The management of network growth with unequal optical splitters might have degraded flexibility. The reach of PON network at certain access points might be highly reduced by the effect of high power split rate. Further research could be carried out so as to compare deployments based either on unequal or equal power splitters. A study that involved variable optical splitters in the context of a bus topology optimisation [62] had a number of follow-up publications. Also, interesting research could be carried out on tunable optical splitters.

Next, a brief account of work concerning the housing equipment for fibre cables and optical power splitters is presented. A variety of housing types emerged due to the following factors:

- the requirement of the variable capacity of boxes, i.e. a relatively smaller boxes tend to be required for low-count clusters of end-users in rural areas;
- a type of cabling system that a box was designed for and the set of functions the box was designed to support;
- a type of passive equipment that is stored inside the box, e.g. optical splitters;
- a type of fibre outside plant system the box was designed for, e.g. underground, aerial.

A few studies on the design of enclosures are presented as follows. The study [63] demonstrated a high capacity splitter node allowing for accommodation of a high number of optical power splitters. This was designed for a dense urban area (Fig.3. in [63]), whereas study [53] demonstrated an aerial and smaller joint fibre closure designed for sparse (rural) areas (Fig.5. in [53]). The authors of work [64] improved the design of a termination box (showed in Fig.5.) so as to make fibre cable termination simpler and more time-effective.

2.2.3 Outside plant fibre deployment techniques

As already mentioned, a relatively high cost of FTTH deployment remained among the major barriers which delayed the fibre roll-out in rural areas. The cost of civil work might dominate the cost of the entire investment. Time-consuming and costly construction work is typically associated with the activity of digging the trenches. The act of considering alternative deployment techniques is crucial and inevitable in the process of improving the time-efficiency of FTTH deployment and the process of decreasing the cost of FTTH deployment. Another important criterion is a high degree of flexibility offered by technology. This should be understood in a broad sense. A broad set of features enable sustainable network growth and gives the freedom to achieve further cost reductions. The following deployment techniques are meant to lead to significant cost savings, as follows:

- micro-trenching – this technique was designed to leverage the solid surfaces of roads, i.e. surfaces made of concrete or asphalt. By using this technique, micro-ducts can be rapidly installed at relatively low depth under the road surface. This is opposed to what the trenching technique consists in [65]. Low depth mitigates the potential damage of other infrastructures both in rural and urban cases. This technique was identified in Norway as the necessity inevitable in the rural FTTH roll-out [40]. A disadvantage of this technique is that the installation of fibre access points (e.g. manholes) might be problematic as the construction work in a solid surface must be carried out. A different technology (e.g. overhead) might be therefore employed if a high frequency of fibre access points is planned. The public use of this technology might be preceded by a governmental approval, as in the case of Norway [40]. Another shortcoming may stem from a relatively lower capacity of micro-ducts. Micro-trenches might provide inadequate space for ducts and fibre cables. Managing the addition of new ducts and fibre access points may be also problematic. It might require careful planning so that already installed ducts and fibre access points (e.g. manholes) become not damaged by a new deployment. Micro-trenching implies an additional work of covering the micro-ducts with a protective layer. Furthermore, the quality of the roads must be adequate.

- ploughing – this technique significantly accelerates the installation of ducts into the ground. Specialised heavy machinery must be employed as it was demonstrated in Denmark [66]. This technique is recommended under the following conditions: a) rural landscape is present, b) a soil type in the area is suitable for ploughing, c) in a situation where long ducting is obligatory. The area planned for the roll-out should be accessible by heavy construction equipment such as excavators. In the process of ploughing, other infrastructures may be damaged. Therefore, the use of ploughing is not recommended in (urban) areas where rich infrastructure was constructed underground. Similarly to micro-trenching technique, the act of adding new ducts and fibre access points alongside existing ducting might be problematic and might involve meticulous planning. The potential duct capacity offered with this technology is relatively higher when compared with the capability of micro-trenching technology. New fibre access points are likely to be deployed with lower difficulty than in the case of micro-trenching. Using ploughing does not entail sealing the ducts as in the case of micro-trenching. Governmental policies might be needed to adopt this technology for public use.

- aerial ducting system [53] or aerial cabling system [58] – approaches that allow for building overhead FTTH networks. Overhead deployment enables high scalability of the network due to the following characteristics: a) an open access to poles, ducts, cables, and enclosures almost everywhere in the infrastructure, b) a high frequency of potential locations where fibre access points can be installed, i.e. subsequent poles are typically positioned in a short distance between each other, e.g. within a span of 70 metres between a pair of poles, c) the deployment of new ducts or cables is virtually no-risk of damage activity. A prominent principle of overhead solution is that it underpins the pay as you grow approach. As a positive effect of that, the initial cost of FTTH deployment can be reduced to a necessary minimum. Conversely, an underground deployment might incur a relatively higher up-front cost, i.e. overprovisioning. The disadvantages of aerial

> systems were identified as follows: a) the cost of maintaining overhead network might be relatively higher compared with the underground deployment because an outdoor aerial deployment is exposed to multiple failures resulting from harsh weather conditions or random accidents, b) safety issues might occur because of inadequate strength or fitting of poles, in the form of falling heavy cables or ducts, c) unsatisfactory aesthetic effect for customers.

In a real-world rural FTTH deployment, all the above technologies could be combined, depending on specific local circumstances, to optimise a local FTTH deployment. Prior to a real-world deployment, network trials could be established and studied, whereby the best deployment practices can be gathered, and the combination of most suitable technologies could be proposed.

2.2.4 Discussion

The main parameters of the optical splitters are size (the number of output and input ports) and whether the power is split equally across ports [67]. While typically PON splitters have one input port, additional input ports can be used for example to provide protection or to give operators the ability to test and detect fibre network failures without re-configuring the physical infrastructure. Splitters are inherently symmetric devices in this sense, although often the additional input ports are not terminated into connectors, in order to reduce cost and footprint. Thus, in rural areas, the operators might consider the trade-off between minimised number of input ports vs. having additional ports for protection and monitoring. Protection schemes for optical access networks were studied in [68, 69]. Another element to consider is the distribution of split size across the different stages, as for example using smaller splitters (e.g., 1:2 or 1:4), in the drop side and non-symmetric split ratios can reduce initial cabling cost [70]. However, using bespoke split power ratios (i.e., different from equal split) would require more complex prescriptive planning. For this reason, in this work we only consider equal power splitters.

Along with the cost minimisation in rural roll-out, it is also important that the deployment strategy assures network scalability. This will help to both develop and grow the network seamlessly, when new dwellings are developed in the area covered by the FTTH network.

Among several deployment techniques, digging trenches is overly costly, although specific techniques, such as micro-trenching and ploughing can be cost-effective, where possible. They may significantly reduce installation cost for duct tubes that can be quickly installed in the surface of roads or underneath the ground. Ploughing has been used in real-world deployment scenarios in Denmark [66], and micro-trenching is under consideration for rural Finnish roll-out [71]. The primary drawback is that they can be deployed only under certain conditions, e.g., non-rocky ground or adequate quality of roads. Moreover, managing network growth in rural scenario with those technologies might be problematic and result in unexpected increase in up-front cost or future cost for upgrade. Demands in rural areas are usually difficult to predict, and network growth can either be addressed by 1) reserving, from day one, larger capacity, above current expected requirements or 2) employing an on-demand approach. The first approach, can become uneconomic for sparse populations, depending on the amount of over-provisioning considered. In addition, while it might work with the ploughing technique, whether micro-trenching can be applied successfully depends on the maximum permissible size of trenches in the roads.

The second approach is also questionable with the techniques mentioned above, because it involves repeating underground deployments at different stages. This might cause the infrastructure already in place to get damaged during the upgrade, and roads might provide no space designated for deploying new micro-trenches in parallel to the existing ones.

Other solutions exist that can be highly cost-effective in rural deployment, such as aerial ducting and blown fibre. They provide time-effective access to the infrastructure and support easy network expansion by allowing modular deployment and on-demand ducting. The authors of [72] demonstrate the advantages of an air ducting system as compared to more traditional cabling systems. Blown fibre also facilitates on-demand network growth, upgrade and repairs. In blown fibre, new fibres can be blown in E-side, D-side or drop sections when a new FTTH service is requested. This represents a common scenario in rural areas where the number of connected end-users may gradually increase. In fact, there exists a wide range of useful improvements in outside plant technologies, some of which are described in [70].

An important improvement in blown cable systems is the possibility to cover longer distance for a drop cable, up to about 1 km, when EPFUs are utilised [73]. Long-reach drops provide significant opportunities and freedom in developing long drop connections cost-effectively for sparse rural scenarios.

2.3 Suitable mathematical formulations

The main goal of this section is to review these algorithms and mathematical formulations, which can serve the formulation of cost-effective PON/FTTH deployment strategies, specifically to be later used to evaluate these optimisation strategies in the rural areas.

Diverse work was carried out regarding FTTH/PON modelling and optimisation. Multiple studies examined various optimisation approaches and considered various constraints in the optimisation models. A precursor work [74] studied a single-stage optical splitting and demonstrated that by using larger power optical splitters such as 1x32 or 1x64, the feeder cable cost could be reduced in urban areas. Multi-stage splitting was also studied in the literature, e.g. in [75, 76]; however, the cited work focused solely on urban environments. Heuristic approaches had to be employed due to the high density of termination points in urban areas. A node-link formulation [77] serves an exact optimisation modelling and optimal routing of fibres. Other approaches such as column generation (e.g. used in [78]) might lead to sub-optimal fibre layout. The trade-off of using node-link formulation is the increased complexity of the model due to the increased number of decision variables compared with the mentioned column generation approach. The authors of [79] proposed a Mixed Integer Linear Programming (MILP) model and considered a PON planning problem where the position of the Central Office (CO) is fixed. A variety of optimisation techniques were used to find out multiple PONs in a geographically restricted area and connect the PONs to the CO. In [80], it was proposed a method that does not assume existing locations for COs. The method was able to find regions where the deployment of PONs (GPON, i.e. up to 32 customers per a PON) could be commercially viable. The method involved clustering, i.e. a modified k-medoid algorithm was employed to identify the optimum partition into 'house clusters'. The clustering attempted to minimise the total length of fibre by optimising the square error, i.e. the sum of squared distances between customers and multiple cluster centres. The authors of that study considered single-stage splitting. The study [76] compared a randomised placement of optical power splitters against a placement based on a clustering algorithm. The outcome of a clustering algorithm based on k-mean algorithm showed how splitter positioning affected the reduction of CAPEX. That paper concentrated on delivering calculations for dense urban areas.

There is a variety of clustering algorithms that could be adapted to serve the optimisation of FTTH and PON networks [81]. Capacitated clustering [82] deserves its own attention in the context of capacity-constrained and tree-like topology networks (FTTH/PON) design.

We utilise this common knowledge in the formulation of clustering algorithms in Chapters 4, 5 and 6, where we combine and build upon the existing algorithms. The design of algorithms is not the primary focus of this thesis. More important is the delivery of significant results through techno-economic studies, which allows to identify cost-effective deployment strategies for rural FTTH roll-out.

We omit the topic of optimisation of the backhaul section of LR-PON in the thesis, but interested reader can examine the past studies on LR-PON network planning, i.e. [83, 84], targeted the minimisation of cable distance in the feeder section of LR-PON. The studies also considered the optimisation of LR-PON protection strategies so as to reduce the overall protection capacity and to optimise the overall fibre cable length.

3 Research gaps and detailed research plan

The following gaps were identified in the literature review in section 2. They will receive consideration in this thesis, and they are planned to be fulfilled.

- the lack of a holistic (both conceptual and analytical) framework for rural FTTH roll-out;
- the lack of studies concerning data mining for the purpose of FTTH deployment (the access section of LR-PON) at the national level;
- the techno-economic studies concerning rural FTTH roll-out are superficial and do not discuss the ways in which FTTH should be deployed in the field, in rural areas;
- the examination involving variable take-up rate was neglected in the rural case;
- there is inadequate work concerning the clustering algorithms centred around the capacitated clustering. This type of clustering plays a vital role in this thesis because it serves the purpose of optimised utilisation of PONs and the purpose of optimised positioning of ODN branches.

The scope of research in this thesis was intentionally confined to the access section of LR-PON, and the backhaul part of LR-PON is excluded from the investigation. The deployment of the access section can be classified as one of the most challenging and urgent issues in the rural FTTH roll-out problem. Nevertheless, the author of this thesis also carried out research devoted to the backhaul section of LR-PON, which evaluated the effect that an extended reach (long-reach) PON has on the consolidation of existing COs. The outcome showed significant reduction in the number of COs in highly rural areas of Ireland, i.e. in the southern counties. However, it was omitted for the foregoing reason. Besides, the backhaul part of LR-PON was already examined in several other studies.

The motivation to focus on the access part stems from the following reasons:

- the planning of the access part deployment is subjected to the effects of variable take-up rate and new developments in rural areas, and therefore, this aspect should be studied in particular in rural areas, whereas the design of backhal section is not directly associated with this particular problem;

- there is lack of thorough techno-economic studies in rural areas that could provide a proof of concept on how to deploy the access part in cost-effective way in rural areas, while the penetration of FTTH is still relatively low in many countries world-wide (e.g. in Ireland);
- potentially and relatively high savings in the deployment cost can be achieved in the planning done in the close proximity to end-users so that the access part gains priority herein in the deployment of the whole LR-PON architecture;
- the implementation of the access part is a gap in the implementation of the whole optical outside plant, whereas the backbone networks are already fibre-based.

As earlier mentioned, the research in this thesis was resolved, i.e., in a broad perspective, to embrace the exploratory research. The exploration of rural FTTH problem is intended to deepen its understanding, help plan more comprehensive studies, or determine a methodology to be applied in subsequent studies. Due to its holistic character, the thesis is anticipated to involve other research types such as analytical or descriptive research. As it was settled before, the exploration was complemented with an another approach, i.e., the top-down approach. This approach determines that the examination of the LR-PON roll-out will commence with a high-level nationwide study towards more thorough investigation targeting some local scopes.

A nationwide LR-PON deployment study will be carried out in the country of Ireland. The plan aims at employing data mining for a wide range of densely and sparsely populated areas. As a result of that, a partitioning of end-users is expected into a specific kind of clusters. The clusters are intended to form the ODN section of LR-PON. The ultimate goal is to cluster a two million set of end-users. Therefore, the design of algorithms must ensure an ample level of their performance so as to satisfy a vast data set of end-users in a time-efficient way. Also, such an objective implies the design oriented towards an unsophisticated, as opposed to complex or highly advanced, clustering algorithms. Therefore, as an option, a parametrised variant of a clustering algorithm is considered. This approach helps to attain a simplified design, but requires the algorithm to be run multiple times so that a series of results can be obtained in order to assess the parameter tuning effectiveness. The results will be evaluated according to the value of optimisation function, i.e., the total amount of fibre cable utilised for the deployment of ODN section. Overall, the study will serve to allow for differentiation between urban and rural LR-PON deployment scenarios from the perspective of the national FTTH roll-out.

A highly rural areas or counties of Ireland will undergo a more in-depth investigation, with the main goal of delving deeply into the FTTH roll-out economics. As already mentioned, a study researching the deployment under varying degrees of take-up rate is considered as an essential element of the rural FTTH roll-out analysis, and thus, it will be conducted in this thesis.

The ultimate objective is to develop a holistic both analytical and conceptual framework which can be eventually applied to demonstrate the viability of the rural FTTH roll-out case. Showing under which particular conditions the case becomes commercially viable is specifically important. In consequence, it will support and drive business decisions leading to further accelerate the progress of rural FTTH roll-out. The research outcome is expected to provide a collection of rural-oriented FTTH deployment strategies and approaches. More importantly, the goal is to devise and discuss the decision-making process that will lead to the commercially viable case. For that purpose, the discussion will target various aspects of the deployment and its key variables, drivers, and related contributing factors. This will offer a step-by-step road map towards 100% FTTH service take-up rate in the rural areas.

4 Nationwide FTTH deployment examination

The work concerning the FTTH roll-out at the national level is present in the literature, however, its typical focus is on the outline of the national deployment plans, and sometimes, it indeed includes a more thorough study in a particular region of the country. Nonetheless, to the best of our knowledge and reviewed state-of-the-art literature, still, there is no such a study that would target the area of the whole country. This kind of a study is essential because it could reveal a number of general answers to FTTH deployment planning in both rural and urban cases, mainly through the examination of various geo-types in the scope of the entire country, such as these appearing in the whole Ireland. On the other hand, from the perspective of this thesis, such a study might have less importance in the countries which have the most portion of population located in the urban areas. Moreover, work on long-reach PON roll-out mainly concentrated on the backhaul section of LR-PON, and the study considering the deployment of access part of it was neglected in the perspective of the nationwide deployment. This section, therefore, attempts to fill the foregoing research gaps, as follows.

Firstly, a potential nationwide deployment of the ODN section of 1024-way-split LR-PON in Ireland undergoes examination. The analysis is carried out to assess the effect of different splitter arrangements on the deployment of ODN section of LR-PON, i.e.: the utilisation of its PONs and the total amount of fibre cable length that is anticipated to cover the whole network. As already mentioned, the clustering algorithm, in this particular study, has a simplified design. For that purpose, the Euclidean distance is selected to serve as the proximity function in the clustering routine. On the other hand, in the subsequent study, the street map distance is employed as the real-world proximity function.

Secondly, a multi-criteria schema and clustering algorithm is proposed to identify cost-effective clusters of end users that can serve a hypothetical Irish telecom operator in the process of planning the expansion of FTTH network, specifically to perform it irrespective of a particular deployment technology. The proposed algorithm employs street map distance as the proximity function to find fibre cable routes planned along the streets, roads, pathways, etc. This indicates the routes where the installation of fibre infrastructure can be typically developed. The outcome of clustering is expected to offer a recommendation regarding the order in which the individual groups of end users, clusters of end users, should be serviced.

4.1 Investigation on the roll-out of the ODN section of 1024-way-split LR-PON

The deployment approach in this section is based on a clustering algorithm that progresses from the locations of end users and aggregates them into specific clusters. Namely, the resulting clusters form the branches of the ODN section of LR-PON. Test scenario involves a real-world data set containing the Global Positioning System (GPS) coordinates of about two million households in Ireland. The outcome of this study is intended to illustrate how the optimal dimensions and positions of the power optical splitters vary across densely and sparsely populated areas. Another intention is to indicate which particular splitter arrangements should be employed depending on the area density so that the number of PONs can be minimised.

The data set of end-users is not publicly available and was provided by Eircom company to carry out the research activities.

4.1.1 Clustering algorithm

In order to yield PON layouts which emulate a realistic deployment, the algorithm processes the end users from the edge of the network, i.e., from the locations of user premises. First, it groups the end users into clusters that represent the coverage area of the last-stage splitters. The maximum distance allowed between the splitter and the end users is set as a parameter of the algorithm. The parameter can be changed so that the area captured by the splitter increases. As a result, the splitter utilisation can be improved. The position of a splitter is optimised to minimise the total fibre cable length (related to ducting and labour costs, etc.). In iterations, splitters are combined into hierarchical stages until a three-stage PON emerges. The clustering algorithm involves polynomial-time algorithms such as kd-tree algorithm [85], and it is implemented in C++. The next sections elaborates on single-stage and multistage clustering routines.

4.1.1.1 Single-stage clustering

Single-stage algorithm is used to cluster a particular number of points and minimise the total distance between cluster members and the cluster centre. The input parameters include: a set of points P_{in}, i.e., the GPS coordinates of buildings to be covered with FTTH service; a parameter R_{max} which indicates the maximum distance between the splitter (the cluster centre) and other lower-stage splitter locations (for the last stage splitter, the locations represent buildings or flats); a parameter S_{ratio} which is the size (i.e. the number of output ports) of the splitter in current stage. The pseudo-code is shown in Fig. 4.1.

Instructions in lines 2-10 initialise the structures. The array D stores building locations sorted by

```
 1: function SINGLE-STAGE($P_{in}, R_{max}, S_{ratio}$)
 2:     $P_{out} \leftarrow set()$                                  ▷ to be returned
 3:     $P_0 \leftarrow anyPoint()$                                 ▷ any point in the plane
 4:     $D \leftarrow array(size(P_{in}))$
 5:     for $i \leftarrow 1, size(P_{in})$ do
 6:         $D[i] \leftarrow pair(EuclidDist(P_0, P_{in}[i]), P_{in}[i])$
 7:     end for
 8:     $sort(D)$                                                   ▷ ascending according distance to $P_0$
 9:     $T \leftarrow BuildKdTree(P_{in})$
10:     $V \leftarrow set()$
11:     for $i \leftarrow 1, size(D)$ do
12:         $P_c \leftarrow D[i].second$
13:         if $P_c \in V$ then
14:             go to line 11                                       ▷ continue loop execution
15:         else
16:             $add(P_c, V)$
17:             $N \leftarrow FindNNeighours(T, P_c, R_{max})$
18:             $sort(N)$                                           ▷ ascending according distance to $P_c$
19:             $N_{closest} \leftarrow SelectClosest(N, S_{ratio})$
20:             $add(N_{closest}, V)$
21:             $C \leftarrow NewCluster(P_c, N_{closest})$
22:             $addNewCluster(C, P_{out})$
23:         end if
24:     end for
25:     $ImproveClusters(P_{out})$
26:     return $P_{out}$
27: end function
```

Figure 4.1: Single-stage clustering.

ascending distance from the initial point P_0. This allows for a systematic clustering, i.e., first the areas that are in the closest proximity to P_0 are marked as visited. This operation is proposed to help minimise the number of clusters. Lines 11-24 form the main loop that executes until all points in P_{in} are marked as visited. The loop begins with the assignment of $D[1].second$ value to P_c. Point $D[1].second$ represents the closest point to P_0. If temporary cluster centre P_c is already associated with some other cluster, the loop continues and selects a subsequent point in list D. Otherwise, set V (tracking visited buildings) becomes augmented with P_c. Routine in line 17 finds nearest neighbours around point P_c within radius R_{max}. Function in line 19 extracts from set N a number of the closest neighbours to P_c, up to S_{ratio} neighbours. The parameter S_{ratio} indicates the maximum number of splitter output ports. Notice that the result of $size(N_{closest})$ can be lower than S_{ratio}, i.e. typically in sparser rural areas, thus deteriorating the utilisation of a splitter. Next, the algorithm calls a routine that forms a new cluster C from $N_{closest}$ neighbours and the cluster centre point P_c. Then, $ImproveClusters(P_{out})$ function optimises the total fibre cable length by rearranging the cluster centres. Namely, for each cluster, it points the building from which the total fibre cable length to other buildings in the cluster is the lowest. Finally, the algorithm searches for such buildings which can be reconnected to a closer splitter. The buildings become reconnected only if a new splitter candidate features spare output ports.

4.1.1.2 Multistage clustering

The multistage algorithm invokes the single-stage algorithm multiple times in order to aggregate higher-stage splitters (nearby end users) into lower-stage ones (closer to the OLT location). The pseudo-code is shown in Fig. 4.2. A separate procedure $ImproveTreeStructure(M_{stages})$ was designed to improve adjacent stages. This function concentrates on clusters at $M_{stages}[s+1]$, and it investigates a cluster Z and all clusters C_j (at $M_{stages}[s]$) that are adjacent to Z. It searches for a new cluster centre for cluster C_j so that this new centre is closer to Z centre. The outcome is approved only if the gain in the total fibre length does not exceed a per-configured threshold (10%). On success, the algorithm includes and enhances Z with $ImproveClusters(Z)$ routine. Also, lower stages are involved into balancing. In effect the positions of the cluster centres are amended towards the root of the tree, provided that the cable distance does not change beyond the threshold. In other words, the algorithm shortens the distances between end users and OLT position and allows for effective reconnections among clusters with $ImproveClusters(Z)$ routine, leading to the improved utilisation of PONs.

```
function MULTISTAGE($P_{in}, R_{maxes}, S_{ratios}$)
    $M_{stages}[1] \leftarrow P_{in}$
    for $s \leftarrow 1, size(S_{ratios})$ do
        $P_t \leftarrow$ SINGLE-STAGE($M_{stages}[s], R_{maxes}[s], S_{ratios}[s]$)
        $M_{stages}[s+1] \leftarrow P_t$
        $ImproveTreeStructure(M_{stages})$
    end for
    return $M_{stages}$
end function
```

Figure 4.2: Multistage clustering.

4.1.2 Test cases

The examination compares a number of different scenarios by running the multistage algorithm with different parameters, i.e. different splitter arrangements. Section 4.1.2.1 elaborates on these arrangements.

4.1.2.1 Splitter arrangements

Several three-stage splitter configurations are summarised in Table 4.1. The splitting ratio is denoted by S_k where k indicates a stage and its value is equal to 1, 2 or 3. The splitters located at the last stage ($k = 3$) are adjacent to end users, whereas the splitter at the first stage ($k = 1$) indicates a PON centre. Radius R^k_{max} limits the range of the fibre cables outgoing from a splitter at a particular stage k. Section 4.1.3.2 discusses results for different R^k_{max} radius values. Splitter sizes above 64 (i.e. the number of output ports) at the third stage are omitted in the investigation because respective splitter arrangements do not lead to an acceptable utilisation of PONs, specifically in sparser areas.

Also, two-stage configurations are excluded from the investigation as they underperform compared to alternatives with three-stage splitting. Notice that $S_1 \cdot S_2 \cdot S_3 = 1024$ is true for each scenario, so that every configuration in Table 4.1 can serve the same number of end users.

First of all, more stages typically leads to a lower cost of deployment, which can be typically observed when long distances are involved in a deployment. Also, in the case of rural scenario, the third stage helps to utilise PONs more effectively, i.e. the PON can be split into a higher number of clusters towards different areas of a spatial plane.

Table 4.1: Splitter arrangements

I.D.	$\mathbf{S_3}$	$\mathbf{S_2}$	$\mathbf{S_1}$	$\mathbf{R^3_{max}}$	$\mathbf{R^2_{max}}$	$\mathbf{R^1_{max}}$
C1	64	4	4	0.5km	2km	10km
C2	32	8	4	0.5km	2km	10km
C3	16	8	8	0.5km	2km	10km
C4	64	4	4	0.35km	1.4km	7km
C5	32	8	4	0.35km	1.4km	7km
C6	16	8	8	0.35km	1.4km	7km
C7	64	4	4	1.4km	7km	7km
C8	32	8	4	1.4km	7km	7km
C9	16	8	8	1.4km	7km	7km

4.1.3 Results and analyses

Section 4.1.3.1 presents a map of the country illustrating the percentage utilisation of PONs spread around the country. In section 4.1.3.2, splitter arrangements are compared for urban and rural cases with respect to the level of PON utilisation as the main criterion. In section 4.1.3.3, the effect of splitter arrangements on the total fibre cable length reduction is discussed.

4.1.3.1 Nationwide PON utilisation density map

The map in Fig. 4.3 shows different PON saturation levels, i.e. their utilisation in terms of end users covered by each PON, according to geographical location. The PONs with the highest utilisation covers about 50% of all households in the country. They are typically located in or around the urban areas, and they are marked as yellow squares on the map. The PONs with the lowest utilisation covers about 5% of all households in the country. Mostly, they can be found in the rural areas, and they are marked with red squares. Figure 4.3 illustrates the outcome for splitter configuration $C9$. This splitter arrangement, as it is outlined in the next section, ensures the highest value of utilisation between all the alternatives. This type of graph is used on purpose to analyse and compare different splitter arrangements with respect to different geo-types, i.e. different population densities.

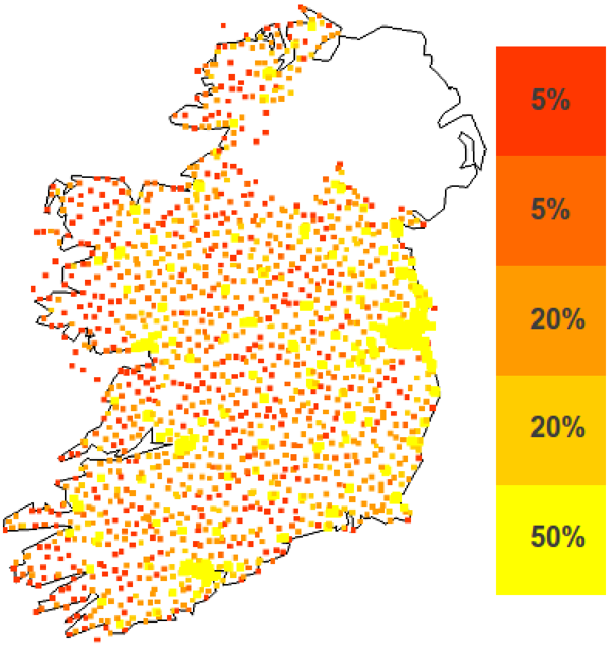


Figure 4.3: Nationwide PON utilisation density map.

Compared with other options (Fig. 4.4), only $C8$ follows the performance of $C9$. However, $C8$ is slightly lower in performance when it comes to the total length of fibre in Fig. 4.5, and that is the reason to present $C9$ herein. The worst performance is pertinent to option $C4$, in Fig. 4.4, and all other options underperform both $C8$ and $C9$.

In fact, the utilisation is determined by many factors. In Chapter 6, further work is devoted to the issue of PON utilisation, i.e. additional mechanisms are discussed and implemented to improve the utilisation.

4.1.3.2 Towards higher PON utilisation opportunities

One of the key economic benefits of PON architectures result from greater sharing of PON access fibre and its components among a large number of end users. Increasing the utilisation of PON, i.e. total number of ports used, is an important objective in FTTH network design. However, there are trade-offs that typically do not allow for achieving this higher utilisation without the expense of longer cable routes, and thus, these two objectives exclude each other as illustrated in the following figure. Fig. 4.4 displays in y-axis the number of PONs required to serve a specific percentage of the total households in the country, for different splitter arrangement options. Notice that the number of end users in the x-axis is sorted with decreasing order according to the PON utilisation criterion. In effect, denser urban areas were placed around the lowest values in x-axis, whereas sparser (rural) areas appear in corresponding and higher positions of x-axis. The graph indicates that in highly populated areas up to about 30% of the total population, the PON utilisation is the same for all splitter arrangements. This situation occurs because the distance between cable distribution points and end user buildings is relatively short (i.e. up to $0.5km$), and therefore, most of the buildings can be grouped into highly utilised clusters, i.e. with a relatively short radius (e.g., $0.35km$) parameter. Notice that the real Euclidean distance in this analysis was reduced by a factor of 1.4 which indicates the average routing factor for Ireland. This simulates the real routes for fibre links which typically follow the layout of roads and obstacles and not straight lines.

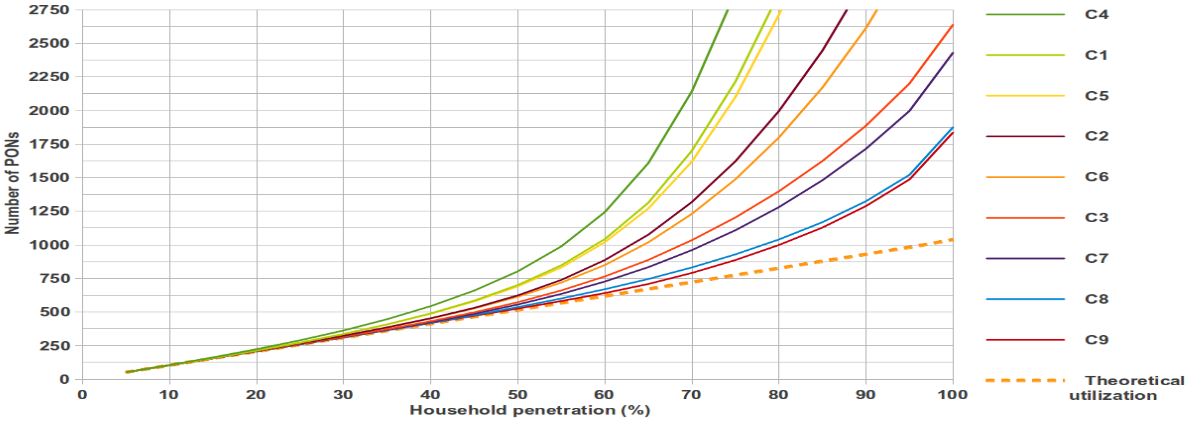


Figure 4.4: Number of PONs required to serve percentage of total households compared for different splitter arrangement options.

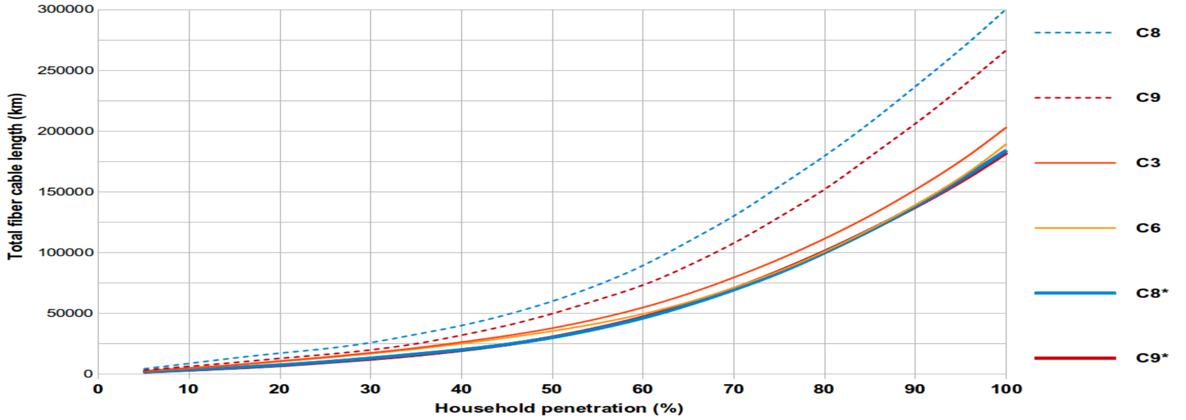


Figure 4.5: Total fibre cable length required to serve percentage of total households compared for different splitter arrangement options (with fibre cable sharing improvement).

The population density decrease has negative effect on clustering larger groups of buildings provided that the reach of clusters is limited. Longer reach of LR-PON leads to an opposite effect and mitigates the negative effect in this type of clustering. For instance, configuration $C4$ features low PON utilisation in sparser areas as locating clusters of 64 buildings within a radius of $0.35km$ is difficult. However, the utilisation can be improved by employing low port count splitters at the last stage $k = 3$ (i.e. $C5$, $C6$ splitter arrangements). These $C5$ and $C6$ options offers higher PON utilisation compared with $C4$ in sparser areas.

Notice that the analysis also includes the scenarios with higher values of R^3_{max} parameter, i.e. the maximum cluster coverage radius for the last stage splitter. Provided that the distribution part of the access network is limited to 10 km, the highest optimal value that was identified for R^3_{max} is roughly $2km$. This value is used to form $C8$ and $C9$ splitter configurations, which offered the highest PON utilisation. These options offers almost theoretical PON utilisation (orange dashed line) up to 60% of household penetration rate. For higher values up to 70% of household penetration rate, the difference is also negligible as shown in Fig. 4.4.

4.1.3.3 Fibre cable sharing improvement

As already mentioned, higher R^3_{max} parameter serves higher PON utilisation but incurs longer fibre cable lengths between the third-stage splitter and end users, thus diminishing the total fibre cable length. This effect is illustrated in Fig. 4.5. However, the fact that fibre cable is designed to enclose more than a single fibre can be used to further improve the total fibre length. An additional step was implemented to select a suitable fibre cable branching points, so that the total fibre length can be minimised through cable sharing. Figure 4.6 depicts cable sharing for a third-stage splitter by branching off 4-fibre cables from shared cable to reach end users. The branching points are positioned in close proximity to smaller groups of end users in order to reduce the total cable length. Fig. 4.5 shows the gain for solutions employing cable sharing (denoted by an asterisk). It can be deduced that a suitable cable branching implementations not only outperform the corresponding splitter configurations (without branching), but they also outperforms those intended to have lower radii with the goal of minimising cable length, such as $C3$ and $C6$ options.

In principle, finding the optimum trade-off between PON utilisation and cable length would involve a relatively more complex cost modelling with fibre cable installation cost in different areas and various PON component costs. On the other hand, the model proposed in this section allows for drawing qualitative conclusions on the suitability of different splitter arrangement options with respect to the population density. By combining the results from Figures 4.4 and 4.5, it is apparent that for urban areas all configurations can work effectively, whereas a few configurations suit rural areas to attain both low cable length and high PON utilisation. These options are namely $C8$ and $C9$, 32-8-4 and 16-8-8 respectively. Finally, the branching algorithm ensures that higher radii of 1.4, 7 and 7 km for the three coverage stages, which was adopted on purpose to increase the PON utilisation, has no negative effect on the total fibre cable length.

4.1.4 Discussion and conclusion

The outcome of analysis shows that in highly populated urban areas the application of different splitter arrangements has literally no effect on the results, whereas the situation is significantly different in sparser rural areas. By increasing the reach of PON and decreasing the split size for the last stage splitter (options $C8$ and $C9$), the PON utilisation could be optimised in sparse rural regions. Also, by

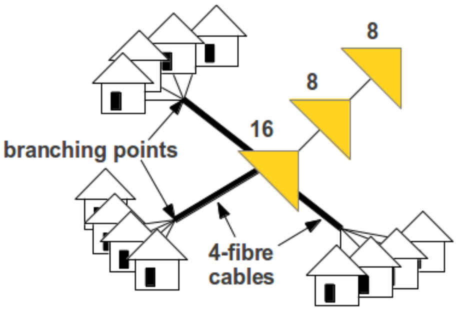


Figure 4.6: Fibre cable sharing diagram.

endorsing an additional degree of freedom for sharing and branching off fibre cables, the final solution could be minimised with regard to the total fibre cable length, while maximising PON utilisation.

More stages, i.e. three stages of optical power splitters in deployment, led to a lower length of total fibre employed in the deployment.

Nevertheless, the methodology presented herein has limitations when it comes to the maximisation of PON utilisation. Further improvements are possible in sparsely populated rural areas, as shown in Chapter 6, through the endorsement of additional mechanisms such as:

- implementation of variable split/reach PONs, depending on the sparsity of the area;
- allowing for unconstrained reach in different splitting stages;
- suitable clustering algorithm (e.g. min-max clustering - described in Chapter 6);
- using of small optical splitters to further partition a PON and increase the utilisation of PON branches.

In fact, it is shown that cable sharing and branching applied in the close proximity to end users has a significant positive effect and results in the reduction of up to 40% in the total fibre cable length. This observation provide motivation to examine another approach, i.e. to use small optical splitters in close proximity to end-users. In this case, instead of using a multi-fibre cable, a shared spur is used and terminated with a small splitter where fibres can be branched off to end users. We further study how such approach affects the total cost of deployment in Chapter 5.

Although this chapter helps to study general design patterns and quantify the effect of their application in rural areas, it is not helpful to assess the cost of a real-world deployment because it measures the total fibre length through independent Euclidean links. Therefore, next Chapters 5 and 6 incorporate street maps in order to compute aggregated costs and more advanced both cost and optimisation models.

4.2 Categorisation of end users according to cost-effectiveness

Compared with previous section 4.1, this section focuses on a generic investigation which is irrespective of a particular technology. The main goal is to give preference to localities where, e.g. FTTH, roll-outs could be more cost-effective from the perspective of commercial operators, which typically have interest in both denser populations and localities situated close to existing (fibre) access points.

The research contribution is to offer a more advanced and fair categorisation schema compared with a basic selection of end-users, depending on partitioning of end-users into 1 km^2 square grid.

The outcome of this section has not been published, and additional work could be provided to further develop the multi-criteria clustering and categorisation schema proposed below.

4.2.1 Multi-criteria clustering procedure

The first criterion relates to the density of population. In this case, the clustering boils down to searching for nearest neighbours around end-user location within a pre-configured radius. For each households u (end-user) in the country, the algorithm finds the number of nearest neighbours within $MaxReach$ distance and saves this value as nn_u. Dijkstra algorithm was adapted for this purpose in such a way that allows to operate on a nationwide graph of streets in a time-effective manner.

The second criterion relates to existing (fibre) access points. Clustering incorporates the distance of end-user to its nearest CO. Dijkstra algorithm was adapted for this purpose.

Fig. 4.7 illustrates the outcome of clustering for $MaxReach = 0.5km$ value. The experiment was also carried out for $MaxReach = 1km$, but this resulted in a less dispersed graph in Fig. 4.7, and therefore, it was not chosen for the presentation. DP in the figure denotes a delivery point, i.e. an end user location.

4.2.2 Categorisation schema

Cost-effectiveness is defined by two criteria above. So, in order to mine end users according to decreasing cost-effectiveness, we should mine these end users which have both the lowest number of neighbours and the longest distance to CO. In other words, we have to mine from the tail in Fig. 4.7. The tail was constrained arbitrarily in Fig. 4.7, but still with the values that have real-world meaning, as explained below.

Fig. 4.7 illustrates a sample selection in which the partitioning is constrained by the maximum number of nearest neighbours (500) for an end-user. This value can be linked to e.g. 512-way-split LR-PON technology. Then, the whole population is divided into 30% and 70% clusters. The value 30% can be linked to the number of households in the rural areas in Ireland. The tail of the graph in red represents the low-preferred localities, whereas the area in red, the high-preferred localities. This split is illustrated in Fig. 4.8 on the map of Ireland. The high-preferred areas correspond to cities and towns, which is not surprising, whereas low-preferred areas to rural areas scattered around the whole country.

Nevertheless, the split or some gradient map can be obtained differently, and cost-effectiveness can be further defined by a higher number of criteria in the clustering by operators. Further development of this schema depends on the data sets that operators could leverage in the data mining process.

Fig. 4.8 shows the distribution of end-users with respect to their both: the density of nearest neighbours and the proximity to the closest fibre access point. Also, it shows the arbitrary clustering into two sets of end-users, which is based on the model with the following assumptions:

- the closest fibre access point is represented by the closest location of a local exchange;
- the number of nearest neighbours is counted within a specific radius from the end-user;
- the radius is relatively short so that it helps to identify neighbours in a common coverage area of a cabinet;
- the clustering prefers those end-users which are located in both denser areas and close to local exchanges as the measure of cost-effectiveness.

Provided only those assumptions, the lesson learnt is that end-users in urban or suburban areas are preferred as a cost-effective choice. The tendency could be reversed by including the assumptions relevant to rural areas. For example, the fact of longer distances could be assumed as potentially beneficial in reducing the cost of travel or transportation for rural communities, and thus increasing the cost-effectiveness.

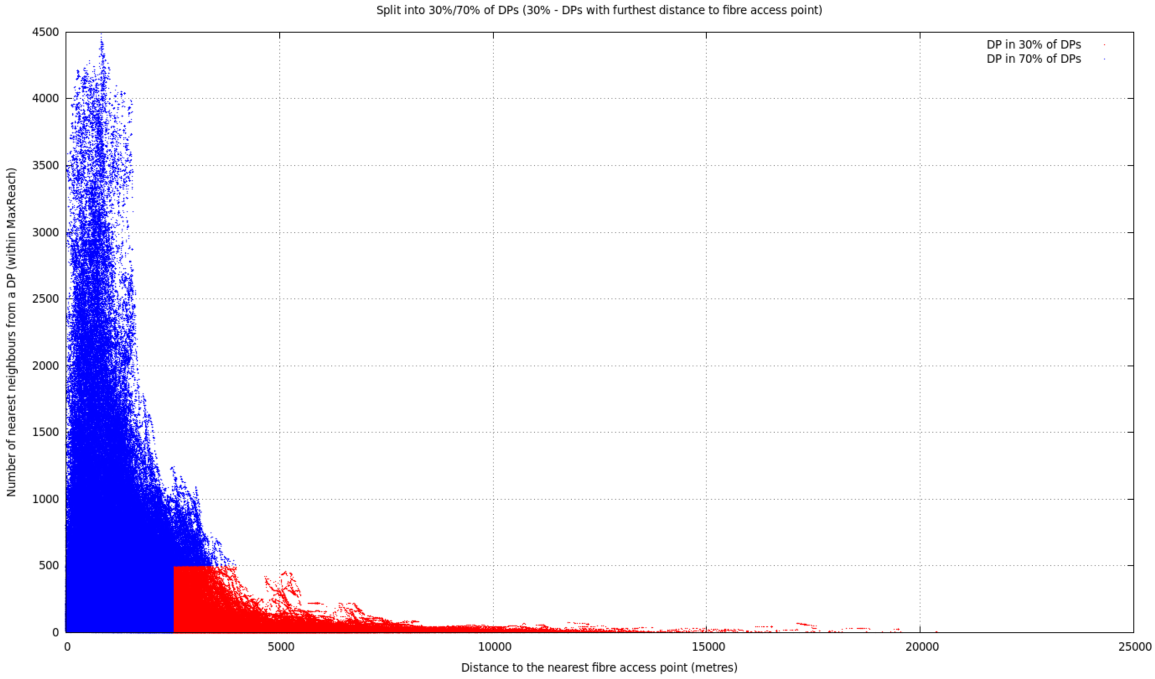


Figure 4.7: The effect of multi-criteria clustering. The split into high-preferred (blue) and low-preferred (red) localities.

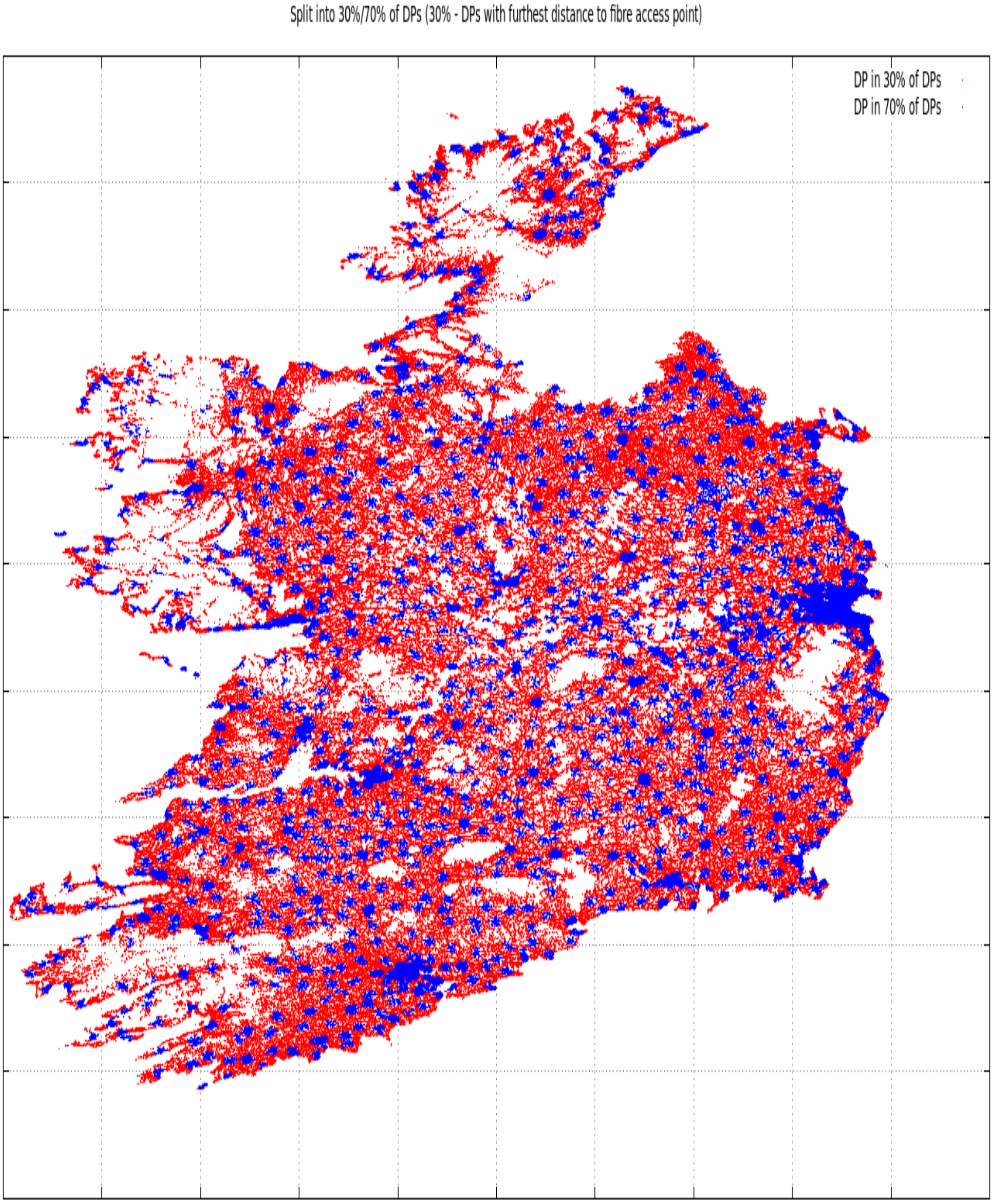


Figure 4.8: Map illustrating the split into high-preferred (blue) and low-preferred (red) localities.

5 The formulation of a least cost solution

There is plenty of optimisation PON modelling work coupling various optimisation approaches as well as considering different constraints in models. A precursor work [74] considers a single-stage optical splitting showing that by using larger splitters such as 1x32 or 1x64, the feeder cable cost can be reduced in urban areas. Conversely, this chapter intends to target rural areas by using small splitters such as 1x4 or 1x8 to reduce the total cost of PON deployment. In fact, the model in this chapter was confined to two-stage splitting due to the complexity of the model and size of covered area. Multi-stage splitting have been already studied in literature, for example in [75, 76]; however, the cited work considers urban scenarios, and it is forced to use heuristic due to the high density of termination points in urban areas. Approach in this chapter instead implements clustering in ILP as opposed to sub-optimal heuristic methods. Also, a node-link formulation [77] is used in this model in order to enable optimal routing of fibres, whereas other approaches such as column generation (e.g. used in [78]) can result in a sub-optimal fibre layout due to the fact that not all variables are generated and used in the optimisation. The trade-off of using node-link formulation is the increased complexity of the model due to the increased number of decision variables compared with the column generation method.

Overall, there is plenty of work that proposes optimal solutions under particular constraints, but it typically lacks a comment on whether the performance of these solutions is close to a hypothetical least cost solution (a lower bound) or a comparison with other formulations available in the literature. This chapter attempts to formulate a least cost solution through a thorough formulation and optimisation carried out under high frequency of potential fibre installation (access) points. Our intention is to discuss our results compared with a hypothetical least cost solution.

As already mentioned, bringing FTTH to rural communities is not trivial due to high initial capital expenditure which stems from low density of end-users and typically the lack of telecommunication infrastructure in place. This chapter proposes a specialised model devoted to rural FTTH planning and the optimisation of the initial setup cost by performing an accurate fibre network planning. This model allows to cover a real-world PON deployment scenario and includes a number of important details into the design. Therefore, a least cost solution can be approached taking into account actual equipment pricing and real geographical coordinates. Key features of the model include the use of multi-fibre blown cables, low-count optical splitters, and street-maps. Evaluation and tests target various rural areas in Ireland. A single test scenario corresponds to an area covered by a cabinet, which indicates a common migration scenario when intermediate step to FTTH is FTTC.

5.1 Methodology outline

A tool was developed for optimising splitter positioning, size and fibre cable routing and sizing. It operates as follows.

5.1.1 Pre-clustering

The clustering of end-users combines kd-tree and k-mean-based algorithms, by means of which end-users are grouped into relatively small clusters (typically 16 or 32). Then, these clusters are further aggregated into larger clusters whose maximum size can be pre-defined and affects the complexity of the model and time for finding the best solution.

5.1.2 Geo-spatial data processing

A processed geo-data (open street-map database [21] and positions of buildings) creates an input graph for optimisation models. Namely, each end-user is projected onto its closest street and potential positions for enclosures are reserved along roads. The frequency of enclosure points in roads is a parameter that also affects the complexity of the model. This step involved an adaptation of an open source tool [86].

5.1.3 Integer linear programming formulations

The input graph feeds Integer Linear Programming (ILP) models. The ILP formulations allow for a single central point (next denoted by C) where all the fibre cables originate. They were implemented to calculate the optimal routes of fibre cables between the end-users and central point C. Subsequently, three related ILP models were defined, as follows:

- **Z1 - point-to-point**
  The model considers single-fibre cables between C (where all 1x16 splitters are accommodated) and end-users. As shown later, this approach is the most costly and impractical in rural areas, whereas it is still likely to be employed in urban areas due to dense end-users population;
- **Z2 - point-to-point (with multi-fibre cables)**
  This approach refines Z1 and employs multi-fibre cables, i.e. single-fibre cables can be aggregated into multi-fibre cables. In effect, a more cost-effective solution can be offered as shown in the result section. A real pricing scheme is used for multi-fibre cables [87];
- **Z3 - small optical splitters with multi-fibre cables**
  This approach refines Z2 and employs small optical splitters (e.g. 1x4, 1x8), which are typically

deployed nearby end-user locations. As a trade-off, large-size multi-fibre feeder cables can be substituted with low-size cables, hence significantly reducing the cost of cabling. This approach is the most cost-effective between three approaches, which is shown later by indicating a gain above 25% compared with the Z2 approach result.

Next section elaborates solely on the ILP formulation for $Z3$ approach; however, formulations for the $Z1$ and $Z2$ approaches can be easily obtained by amending the $Z3$ model.

As shown below, the main advantage of model $Z3$ over $Z2$ is its cost-effectiveness in sparsely populated rural areas. $Z3$ involves small optical splitters, which helps to eliminate long spurs, i.e. multi-fibre cables leading to sparse clusters of rural end-users, and in effect, a lower total cost of deployment can be achieved. Also, $Z3$ implies that splitters have to be located near the end-users. This fact makes the further growth of the network more seamless compared with model $Z2$.

5.2 Mathematical formulation

The following section elaborates on $Z3$ approach ILP formulation. Symbols z_1^*, z_2^*, z_3^* denote the optimal solutions to optimisation problems $Z1$, $Z2$, and $Z3$, respectively. Since $Z2$ surpasses $Z1$, and $Z3$ surpasses $Z2$, it can be expressed as $z_1^* = min(z_1) \geq z_2^* = min(z_2) \geq z_3^* = min(z_3)$, which occurs for all test scenarios that were investigated herein. The z_2^* and z_3^* values indicate the optimal solutions to $Z2$ and $Z3$ problems. The difference between these approaches, i.e. the gap defined as $gap_2 = z_3^* - z_2^*$ is used to measure the importance of small optical splitters approach (i.e. approach $Z3$).

The entire formulation was split into drop and feeder subsections (5.2.1 and 5.2.2) on purpose because the maximum blowing distance for both sections differs in each one. Moreover, drop fibres may not be intended to be aggregated into multi-fibre cables (as opposed to feeder fibres) since individual end-users may join the network at different times.

The ILP is formulated as follows:

- **Sets:**
  - $p \in P$ - set of premises (i.e. SFUs);
  - $v \in V$ - set of vertices (**access points**): a single access point denotes a possible location suitable for an enclosure deployment, i.e. where optical power splitters, cable splices and joints can be accommodated. The frequency of these access points along roads is set through a parameter and affects the complexity of the model;
  - $e \in E$ - set of edges. In fact, an edge represents a street segment, which comprises a connection between two adjacent access points;
  - $w \in W$ - a set of multi-fibre cable sizes, i.e. $W = \{0, 2, 4, 8, 12\}$ (0 is included to support mathematical modelling);

  - $s \in S$ - a set of possible sizes of optical power splitters, i.e. $S = \{1, 4, 8, 16\}$ (1 is an exception and denotes a splice);
  - $t = (v_1, v_2) \in T$ - a set of trunks. A single trunk forms an abstract link between a pair of access points, which is used to model multi-fibre cables (more details in section 5.2.2.2). Aiming at lowering the running time, the total number of possible trunks must be reduced, i.e. a link t is only counted in the model if $dijkstra(v_1, v_2) \leq MAX_{feederblow}$;
  - $i \in I = \{0, 1, 2\}$ - a set of indices to accommodate a number of splitters at a particular access point $v \in V$;

- **Supporting algorithms:** $dijkstra(v_1, v_2)$ - standard shortest path algorithm, i.e. it returns the shortest path between v_1 and v_2 access points (in meters);

- **Constants:**

  - S_v - the central access point C (e.g. a cabinet);
  - $MAX_{dropblow}$ - the maximum drop fibre cable blowing distance (i.e. 1km);
  - $MAX_{feederblow}$ - the maximum feeder cable blowing distance (i.e. 2km);
  - $MAX_{splices}$ - the maximum number of fibre splices between S_v and any of the end-users;
  - C_{drop} - unit cost of drop fibre cable (per meter);
  - C_{port} - unit cost of optical splitter port;
  - $C^{w}_{multi-cable}$ - unit cost of multi-fibre cable sized w (per meter);
  - $C_{enclosure}$ - an enclosure deployment cost;
  - $conn(p)$ - a set of access points serving a premise p. Sometimes, a premise is located nearby a number of streets and alternative access points in these streets can be used to connect end-user;
  - E^{e}_{len} - the length of edge (a street segment) e (in meters);
  - C^{v}_{p} - cost of constructing a link between a premise p and an access point v. Its value depends on various factors, e.g. the distance from a premise p to an access point v (illustrated by a red line in Fig. 5.1);
  - PV_{pv} - equals 1 if an access point v is available to a premise p (Dijkstra is used to determine the value of $PV_{pv}, p \in P, v \in V$);
  - $MAX_{16} = \lceil \frac{|P|}{16} \rceil$ - the minimum number of optical splitters sized 16 necessary to cover a number of $|P|$ premises. Due to previous findings in [42], a size of the last stage optical splitter is determined to 1x16. This size is suitable for sparse rural areas, which can be concluded from work [42];

- **Variables:**

  - $t_{vp}(binary)$ - equals 1 if a premise p is connected to a drop cable through access point v. For simplicity, assumption is that $|conn(p)| = 2$, i.e. the set of access points includes only a pair of access points, which are on the street adjacent to a premise. This collection can be further improved by a specialist;
  - $f_{ep}(binary)$ - equals 1 if an edge e is used in the route of the drop cable to serve a premise p;
  - $c_{v_1v_2we}(binary)$ - equals 1 if an edge e is used in the route of a multi-fibre cable (sized w) which is contained within trunk $t = (v_1, v_2)$;
  - $a_{vs}(integer)$ - measures a number of optical splitters sized s and deployed at access point v;
  - $a_v(binary)$ - equals 1 if the deployment of enclosure is present at access point v;
  - $l_{vsi}(binary)$ - equals 1 if a splitter i, whose size is s, is deployed at access point v;
  - $t_{vsiv_1v_2}(binary)$ - equals 1 if a trunk (v_1, v_2) is employed to provide a connection between a splitter (s, i) (located at access point v) and the central access point S_v;

- **Objective function:** The objective function minimises the total PON deployment cost, which comes from: the cost of drop fibre cable (z_{3drop}), the cost of multi-fibre feeder cables ($z_{3feeder}$), and the cost of enclosures and optical splitters (z_{3equip}). The objective function is defined as follows:

$$z_3^* = min(z_3) = min(z_{3drop} + z_{3feeder} + z_{3equip}) \tag{5.1}$$

, where z_{3drop}, $z_{3feeder}$, z_{3equip} are respectively defined by the following equations:

$$\sum_{e \in E} \sum_{p \in P} C_{drop} \cdot E_{len}^{e} \cdot f_{ep} + \sum_{p \in P} \sum_{v \in conn(p)} C_p^v \cdot t_{vp} \tag{5.2}$$

$$\sum_{e \in E} \sum_{t=(v_1,v_2) \in T} \sum_{w \in W} E_{len}^{e} \cdot C_{multi-cable}^{w} \cdot c_{v_1v_2we} \tag{5.3}$$

$$\sum_{v \in V} C_{enclosure} \cdot a_v + \sum_{v \in V} \sum_{s \in S} C_{port} \cdot a_{vs} \cdot s \tag{5.4}$$

- **Constraints:**

5.2.1 Drop section of PON

Each of the premises $p \in P$ is connected to a feeder section of the PON through a drop fibre cable. Drop fibre cables are modelled through node-link formulations (f_{ep} variables). A drop cable is connected to a feeder section of the PON through an access point located somewhere in the adjacent streets (equation (5.5)). Then, the drop cable must be joined together with a feeder cable (equation (5.6)). A joint either represents: a) a splice ($s = 1$) or b) an optical splitter (1x4 or 1x8, $s = 4$ or $s = 8$). Inequality (5.7) ensures that the capacity constraint of optical splitters is not violated. Equation (5.8) describes the node-link formulations of drop fibre cables, while constraint (5.9) delimits the maximum length (blowing distance) of drop cables.

$$t_{v_1,p} + t_{v_2,p} = 1, p \in P, \{v_1, v_2\} = conn(p) \tag{5.5}$$

$$\sum_{s \in S} \sum_{v \in V, PV_{vp}=1} l_{vsp} = 1, p \in P \tag{5.6}$$

$$\sum_{p \in P, PV_{vp}=1} l_{vsp} \leq s \cdot a_{vs}, s \in S, v \in V \tag{5.7}$$

For $v \in V, p \in P, (v_1, v_2) = conn(p)$:

$$\sum_{e \in \delta^+(v)} f_{ep} - \sum_{e \in \delta^-(v)} f_{ep} = \\ = \begin{cases} -t_{v_1 p} + \sum\limits_{s \in S, PV_{vp}=1} l_{vps}, v_1 = v \\ -t_{v_2 p} + \sum\limits_{s \in S, PV_{vp}=1} l_{vps}, v_2 = v \\ 0, PV_{vp} = 1 \end{cases} \tag{5.8}$$

$$\sum_{e \in E} E^e_{len} \cdot f_{ep} \leq MAX_{dropblow}, p \in P \tag{5.9}$$

5.2.2 Feeder section of PON

The feeder section (D-side section) of the PON serves to connect the drop section to the central access point (cabinet in this case) by means of small optical splitters or multi-fibre cables as follows.

5.2.2.1 Optical splitters

The number of splitters or splices (a_{vs}) at v determines the number of fibres outgoing from v (inequality 5.10). In fact, this inequality serves to enable node-links (5.13), i.e. when $l_{vsi} = 1$, a node-link associated with l_{vsi} is enabled. The node-links allow to form feeder fibres, which reach to and terminate at the central access point S_v.

The number of splitters required to cover a given area is intended to be minimum (examine the definition of MAX_{16} constant above), and inequality (5.12) fulfils this requirement. Because design also allows for two-stage splitting, e.g., a splitter 1x16 can be further replaced by a cascade, i.e. a chain of 1x2 and 1x8 splitters (examine [76] to comprehend power budget constraint). Moreover, the inequality (5.11) constrains two-stage splitting to satisfy the maximum number of available 1x16 splitters MAX_{16}.

$$a_{vs} - (i - 0.5) \leq l_{vsi} \cdot M, v \in V, s \in S, i \in I \tag{5.10}$$

$$\sum_{v} a_{vs}/s \leq NS_s, s \in S \setminus \{1\} \tag{5.11}$$

$$\sum_{s \in S \setminus \{1\}} NS_s \leq MAX_{16} \tag{5.12}$$

5.2.2.2 Trunks

Trunk $(v_1, v_2) \in T$ is a virtual directed link that originates at v_1 and terminates at v_2. A trunk serves to measure the number of feeder fibres routed through a pair of access points $(v_1, v_2) \in T$. This value is used to dimension the multi-fibre cables, in the next section, to a particular size. The maximum number of fibre splices (on the path that forms a long feeder link) can be limited and configured through inequality (5.14). Node-links, i.e. feeder trunks, are defined as follows: for $v \in V, v \neq S_v, s \in S, i \in I, v' \in V$:

$$\begin{aligned} \sum_{(v_1,v_2) \in T, v_2 = v'} t_{vsiv_1v_2} - \sum_{(v_1,v_2) \in T, v_1 = v'} t_{vsiv_1v_2} = \\ = \begin{cases} l_{vsi}, v' = S_v \\ -l_{vsi}, v = v' \\ 0, otherwise \end{cases} \end{aligned} \tag{5.13}$$

$$\sum_{(v_1,v_2) \in T} t_{vsiv_1v_2} \leq MAX_{splices}, v \in V, s \in S, i \in I \tag{5.14}$$

5.2.2.3 Multi-fibre cables

Having the count of fibres routed through a trunk $(v_1, v_2) \in T$, the size of multi-fibre cables can be determined as follows, for $w \in W, (v_1, v_2) \in T$:

$$\sum_{s \in S} \sum_{i \in I} \sum_{v \in V} t_{vsiv_1v_2} \leq c_{v_1v_2w} \cdot w + (1 - c_{v_1v_2w}) \cdot M \tag{5.15}$$

, and by assuming that only a single multi-cable can be used for a pair $(v_1, v_2) \in T$:

$$\sum_{w \in W} c_{v_1 v_2 w} = 1, (v_1, v_2) \in T \tag{5.16}$$

Every single multi-fibre cable follows its individual route resulting from a node-link formulation: for $(v_1, v_2) \in T, w \in W, v \in V$:

$$\sum_{e \in \delta^+(v)} c_{v_1 v_2 w e} - \sum_{e \in \delta^-(v)} c_{v_1 v_2 w e} = \begin{cases} -c_{v_1 v_2 w}, v = v_1 \\ c_{v_1 v_2 w}, v = v_2 \\ 0, otherwise \end{cases} \tag{5.17}$$

, while the length of multi-fibre cable is limited to the maximum fibre blowing distance:

$$\sum_{e \in E} c_{v_1 v_2 w e} \cdot E^e_{len} \leq MAX_{feederblow}, w \in W, (v_1, v_2) \in T \tag{5.18}$$

5.3 Tests

The models were implemented in C/C++ and solutions found by CPLEX 12.5.1 solver (CPLEX callable library) within 1 hour time limit. The solver's parameter related to moving the best bound was tuned in order to improve solver's optimality proving process, thus reducing the running time.

All solutions were optimal within 1 hour time limit, except the case $C = 34$:

- $Z2$ is optimal;
- $Z3$ is feasible with a low gap (between the linear relaxation and the best integer solution) equal to 0.64%.

Tests target three different rural areas with different population distributions and street layouts as shown in Fig. 5.1. All approaches are compared in Fig. 5.2. Since it is evident in Fig. 5.2 that the approach $Z1$ is the least cost-effective, the further comparison focuses on $Z2$ and $Z3$ approaches.

5.4 Discussion

The most significant gain (value of gap^*_2), i.e. about 27% cost improvement, is evident in Fig. 5.2 for the case where $C = 10$. This large improvement can be attributed to long distances stretching between the end-users and the central access point (about 6 km). In this situation, the use of small power optical splitters allows to reduce large-size multi-fibre feeder cables to smaller ones, thus reducing total cabling cost significantly. In the case where $C = 34$, the gap gap^*_2 is about 15%. For the last case, the gap ranges within 10% - 25%.

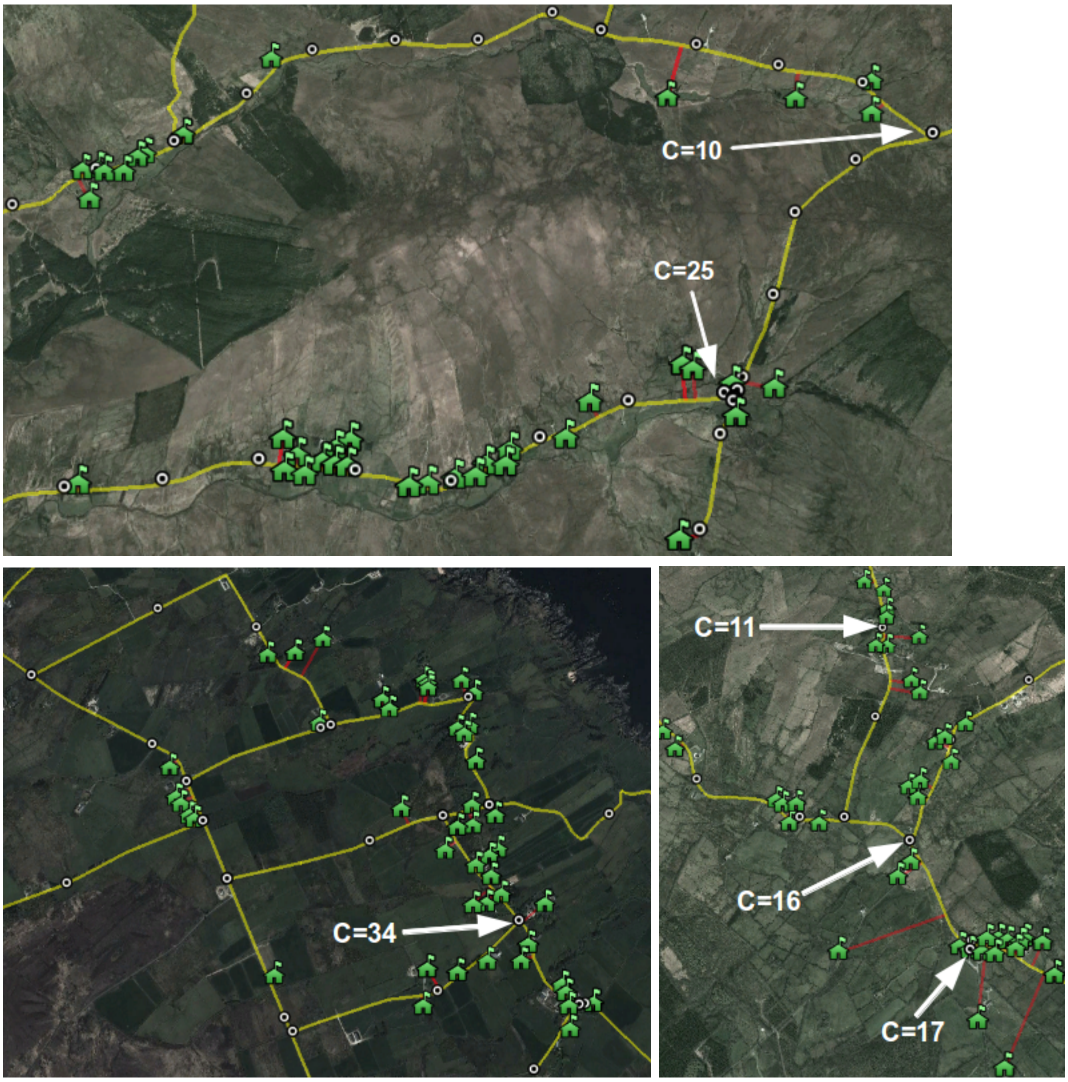


Figure 5.1: Three different rural scenarios. Legend: a) white circle indicates a possible location for enclosure deployment b) red line indicates the shortest link between a premise and the street.

Moreover, the findings signify a least cost solution because the final solution generally consist of 4-fibre cables, i.e. the total cost cannot be further reduced because smaller cables such as 1-fibre or 2-fibre cables have the same cost as 4-fibre cable (examine [87]).

5.5 Conclusion

This chapter addresses the problem of finding a least cost solution to the FTTH deployment problem in rural areas and realistic deployment scenarios for Ireland. Three Integer Linear Programming (ILP) formulations are proposed for rural scenario together with suitable deployment technologies for this type of scenario. It was shown that by employing small optical power splitters near the locations of end-users, the size of feeder fibre cable could be reduced, thus significantly improving the initial investment fibre cable cost in excess of 25%.

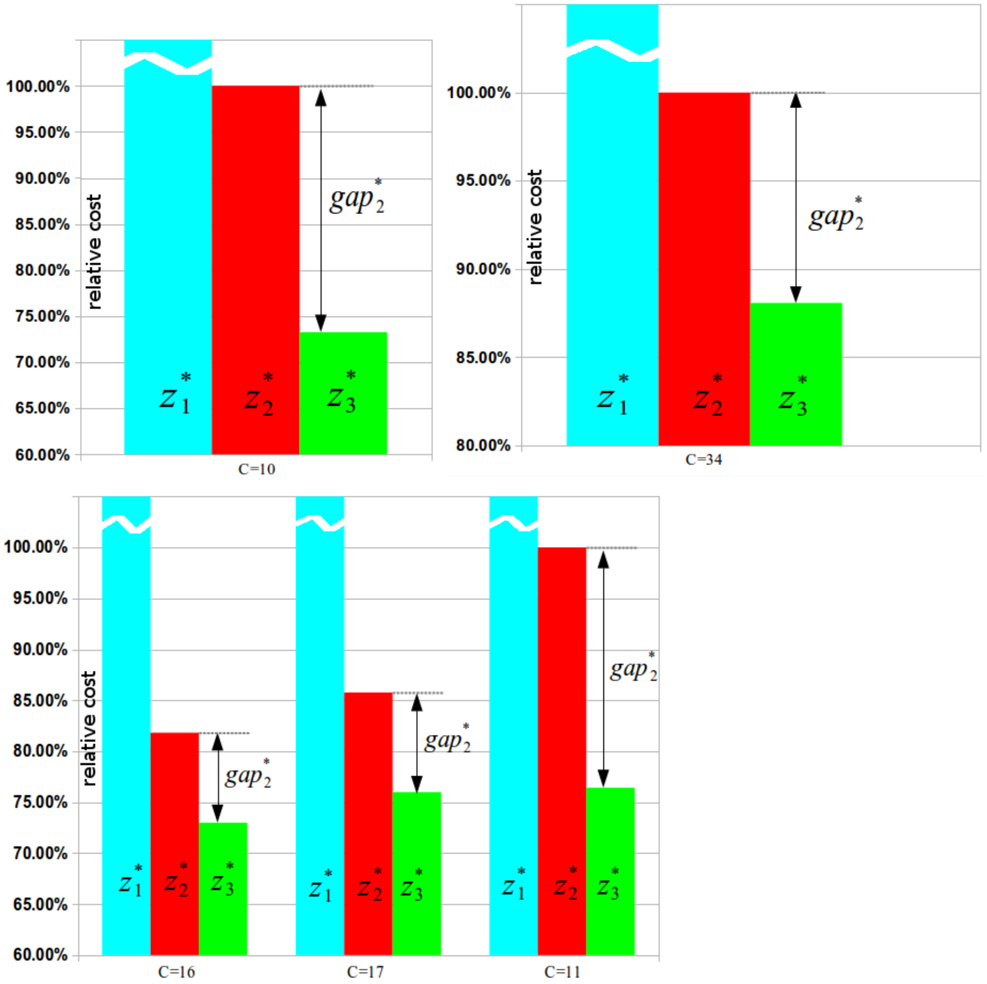


Figure 5.2: The cost performance comparison of deployment approaches $Z1$, $Z2$ and $Z3$. The importance of the approach involving small optical power splitters $Z3$. The gap measures the gain, and C indicates the central access point location (as shown in Fig. 5.1).

This chapter covers deployment within a cabinet area. Next chapter will target larger areas served by a local exchange and additional parts of the Optical Distribution Network, up to the location of the optical amplifiers (i.e., the current location of the local exchange).

6 Trading off upfront cost under uncertainty of user take-up rate

Although the increased deployment cost with respect to expected revenue is the main barrier to FTTH roll-out in rural areas, the problem is further exacerbated by the uncertainty associated with end-users take-up rate, as demonstrated in this chapter. The randomness bound up with the subscribers service take-up yields considerable fluctuation and escalation in the total cost of deployment. This adverse and varying environment impedes the development of firm business cases and renders potential investors and incumbent operators more reluctant to deploy FTTH access networks in rural areas.

In this chapter, a holistic framework for examining the real-world FTTH deployment covered by an area of CO is presented, taking as case study one of the most rural counties of Ireland. Also, an in-depth techno-economic analysis was carried out to identify the methods more applicable in the rural scenario. The cost-effectiveness of FTTH deployment was analysed with respect to solutions that provide different levels of upfront investment risk and uncertainty in customers take-up rates. For example, it was illustrated how to manage the low take-up rate case to make it more profitable, i.e. by adopting a strategy that favours lower up-front cost at the expense of higher network setup cost.

By definition, take-up rate is measured as the number of customers connected to the number of customers passed (coverage). Typically, the distance between a customer passed and the nearest fibre access point varies up to a few kilometres in the rural case.

Rural roll-out requires careful planning to make the deployment commercially viable. Therefore, this chapter investigates the risk associated to different PON deployment strategies, focusing on rural areas, with respect to different levels of FTTH service take-up rate.

The roll-out under investigation makes use of the LR-PON architecture, as defined in [13, 88], which adopts split ratios of 512 and maximum optical reach above 100 km. To recap, the saving brought by the architecture can be summarised as follows:

- reduced number of OLT cards through the increased physical split;
- reduction in the amount of fibre cables required due to multi-stage splitter design in the ODN;
- a considerable reduction in the number of COs/local exchanges;

- the reduction of electronic interfaces through the convergence of the PON with the metro/regional network [89].

The work in this chapter focuses on the following trade-off: (I) achieving optimal long-term deployment cost, but assuming a known expected take-up rate (due to optimal resource utilisation and sharing) versus (II) sacrificing some optimal resource management, in order to reduce short-term network up-front cost (which reduces the risk associated with lower take-up rate than expected).

The author believes that achieving objective (II) is generally key to succeed in rural areas. Moreover, building a network with the lowest up-front cost is critical to approach the viability of the network operation. Indeed, while the first approach (I) has been considered for denser areas, where the favourable economics allow for larger margins in take-up rate uncertainty, the study in this chapter indicates that the second approach, i.e. (II), implemented through the deployment strategy proposed in this chapter, is generally preferable for rural roll-out. The numerical results show that the up-front cost can be significantly reduced at the early stage of the FTTH network development.

6.1 "Long drop" connection methods

The main goal of this section is to describe a number of deployment methods by indicating their suitability for low-risk and high-risk service take-up scenarios. For the lower risk scenarios, the aim is to achieve the optimal deployment cost through optimal resource utilisation and sharing. This is possible because planning in advance is feasible due to the expectation of high take-up rate. The urban case tends to represent a lower risk scenario, as the lower deployment cost (due to higher user aggregation) poses lower economic risk under uncertainty in take-up rate. In addition, historically, take-up rate has been relatively high. For instance, suitable business modelling and regulations enabled FTTH connections with speeds of up to 1 Gigabit-per-second in Stockholm to 90% of all households and nearly 100% of all companies [90]. The roll-out took two decades in Stockholm. On the other hand, in higher-risk scenarios (for example rural areas, where users are much further apart), the optimal resource management is sacrificed in order to reduce network upfront costs. This approach is required to make the network operation cost-effective from the early stages. The rural roll-out can be classified as a high risk take-up scenario. Indeed, this is the part of the network that typically requires government subsidy.

Three different long drop deployment strategies, i.e. connection methods (*CMs*), are reported in Fig. 6.1. The deployment operations is divided into two major stages: Stage 1, the "passing stage", where the operators deploy the FTTH service in an area, but only up to the D-side section; Stage 2, the "connection stage", where the operator finalises the connection in the drop side, once the end user takes up the service. The capability of sharing resources mainly depends on how the ducting is shared between the drop and D-side fibre sections (depicted in Fig. 6.1). In this chapter, aerial Blown Fibre Tube (BFT) technology is used for ducting (more details in Section 6.3). To investigate the trade-off,

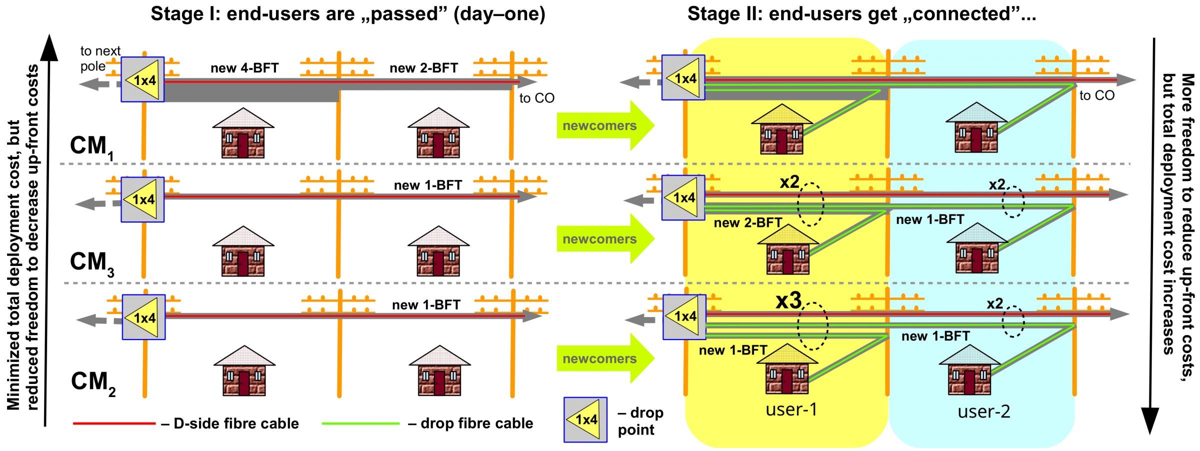


Figure 6.1: "Long drop" connection methods: resources sharing is defined primarily through how ducting is shared between D-side and drop sections. This figure represents an effect of clustering described next in Section 6.2 and Fig. 6.6.

the difference between the passing and connecting costs is measured, as a function of end-users take-up rate. In order to make the simulation realistic, an assumption is made that end-users join the network in a random order. In the example in Fig. 6.1, user-1 and user-2 join the network at different times, and the figures show the different fibre installations used for the three different models.

- *CM1* - In *CM1*, both sections share ducting in Stage I and Stage II, resulting in the most cost-effective deployment.

  However, as a downside, *CM1* exhibits an increased network start-up cost, i.e., the passing cost, since the whole ducting infrastructure is required to be installed during network set-up. Therefore, this method is suitable for a low-risk take-up scenario where the issue of high start-up expense can be offset by the lower overall costs or high take-up rate.

  In summary, *CM1* option offers the lowest fibre deployment cost, but it incurs the highest upfront expenditure.

- *CM3* - This option considers a separate ducting for both sections. Still, sharing is considered for the drop section duct in Stage II, which contributes to the total cost optimisation. It is more expensive compared to *CM1* because the installation of new ducts incurs higher labour expenses (see Fig. 6.1). However, it offers the ability to postpone the cost of deploying drops until user-1 or user-2 in fact joins the network. In Fig. 6.1, first, a new 2-BFT duct is installed when a user gets connected, and a new 1-BFT drop deployment to user-2 or user-1 is postponed, whenever this takes up the service.

- *CM2* - There is no duct sharing as opposed to *CM1* and *CM3* (compared in Fig. 6.1). Therefore, this option incurs the highest total deployment cost due to costly labour work resulting from the increased number of independent ducts (see Fig. 6.1). On the other hand, the separation of

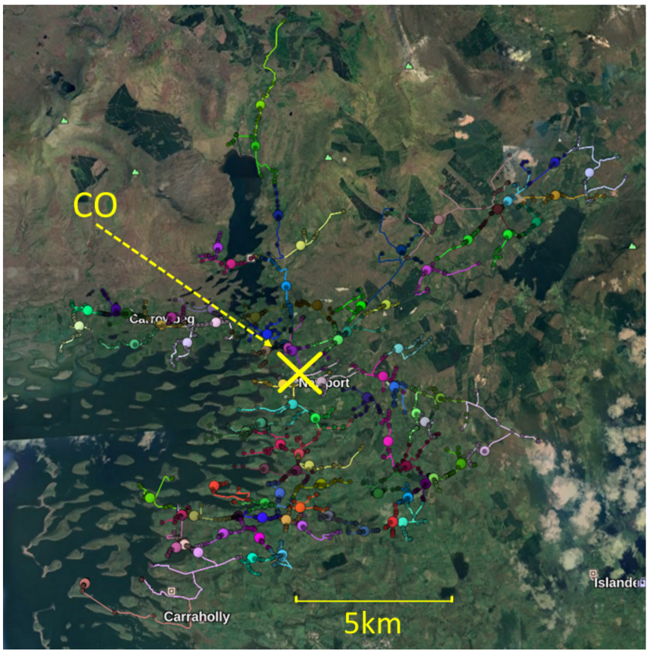


Figure 6.2: The results in the area within the administrative borders of a local exchange in Newport, Mayo county.

the drops enables their independent deployment, and connecting a new customer can be done on demand. This provides the highest flexibility in postponing up-front expenditures. In the example in Fig. 6.1, the duct provisioning to user-2 can be delayed until this user joins, as its connection is independent on user-1 ability to take up the service.

6.2 Modelling

This section offers insight into the design of the optimisation methodology that is modelled around the physical infrastructure presented in Section 1.2 and Fig. 6.1. The examination in this chapter targets one of the most rural areas in Ireland, and considers 1416 end-users' dwellings. These typically consist of single-dwelling units for each customer, i.e. houses [91], distributed over an area of about 330 km^2, shown in Fig. 6.2. Its layout will consist of a tree topology, with optical splitters placed at multiple stages in close proximity with roads. In the case of LR-PON, the four 128-way-split sections below the 4x4 splitter are branches within the ODN, and they are not PONs in their own right.

The scenario considers an area within the administrative borders of a local exchange, currently operating in Newport, Mayo county (Fig. 6.2). This assumption has a practical justification, since the population in the area is more dense in the town centre with a gradual decline as one moves outside the town. In the model, different fibre routes are branched from the current location of the CO building, where a gradual expansion of fibre network can occur from the town centre outwards, towards the rural and more remote outskirts. Overall, it is common for work on fibre deployment strategies to target specific geographical areas [92, 93]. This area was selected manually, i.e. without comparing numerical properties of all COs in Mayo county. Still, the aim was to select an area that indeed represents a rural case, i.e. with end-users scattered around and not solely concentrated in suburban and urban areas.

In the following subsections, the optimisation framework is described. First, a foundation that underpins a heuristic and a clustering algorithm was defined, i.e., a homogeneous multi-stage PON design. It is described how it differs from the standard multi-stage PON design, and how one can benefit from such a distinct approach. Next, this homogeneous design is adopted to formulate a novel clustering algorithm. Upon this single-stage clustering algorithm, a heuristic could be developed, i.e. a multi-stage clustering algorithm. Also, the factors that motivate the heuristic design were explored.

6.2.1 Homogeneous multi-stage PON layout

A homogeneous layout assumes the same splitter size across all similar PON stages (e.g., say having all 1x8 splitters across all stage-2 splitters), whereas the standard design assumes that splitters of different sizes can be deployed on any given location. Homogeneous layout is assumed because this simpler design simplifies roll-out, deployment and the algorithm design. In addition, adopting a homogeneous design allows to address broader questions, as will be shown in Section 6.4, such as the overall effect of different split sizes.

Table 6.1 lists all homogeneous arrangements within a 128 way ODN branch that are examined in this chapter. First, the explanation of the notation used for multi-staging follows. A configuration denoted by *4x16x2+* assumes the use of a 1x4 splitter at the last stage (i.e., drop point), while using a *1x16* and *1x2* splitters at the two preceding stages. The plus sign indicates that multi-fibre cable aggregation is additionally performed to increase sharing and cost reduction. The aggregation is not assumed by default because it implies that stages must be deployed at once. Without the cable aggregation, the 2nd stage can be deployed after the 1st stage, according to the business plan. The aggregation occurs within a single section, i.e. either D-side or E-side. Aggregation is not assumed for the drop side, as this typically is installed only when a user requires to get the FTTH service.

The setting in Section 1.2 in Fig. 1.3 allows 128-size branches in the ODN below the CO 4x4 splitter; hence, each configuration in Table 6.1 gives an overall split size of 128 (e.g., 4x16x2=128) assuming 10 km reach, with each branch divided in three split stages (in addition to the 4x4 splitter at the LE). However, since the support for variable length and split size is assumed, branches with smaller overall split size can be used to further extend the reach to cover the sparsest rural areas. If the reach beyond 10 km is needed, smaller split size branches that have a lower total split can be used. For instance, a 8x4x4=128 branch would be reduced by half to 8x4x2=64 in order to increase its reach to 20 km. By reducing any branch size split by a factor of 2, one gains about 3 dB of optical budget, which in the field translates into approximately 10 km increase in optical reach that can be used on that specific branch. This methodology is implemented in the heuristic in Section 6.2.3.

Table 6.1: Homogeneous splitter configurations

the last splitter size	homogeneous splitter configurations
64	64x2
32	32x2x2, 32x4
16	16x4x2, 16x8
8	8x4x4, 8x8x2, 8x8x2+
4	4x8x4, 4x4x4x2, 4x2x8x2, 4x16x2, 4x16x2+
2	2x16x4, 2x16x4+

Figure 6.3: Sample outcome of fixed-size single-stage clustering, a number of 16-size clusters assembling separate end-users groups. A 16-size cluster denotes a drop section equipped with 1x16 power optical splitter. Every round coloured sphere indicates a cluster centre and the place where drop cables can be branched off from a splitter.

6.2.2 Fixed-size and street-map-based clustering algorithm

Based upon the methodology described in the previous subsection, a novel fixed-size and street-map-based clustering algorithm is proposed. The clustering algorithm returns equal-sized clusters (see Fig. 6.3), for each stage (with the exception of the last cluster grouping with leftover elements). The algorithm solves a variant of a general problem known as Capacitated Clustering Problem (CCP) which is nondeterministic polynomial time (NP-hard) problem. A novel initialisation method is proposed in Fig. 6.4, so that a promising initial solution can be obtained, and thus, a costly polishing phase in Fig. 6.5 can be mitigated.

The clustering algorithm operates over distances that are calculated using accurate street map information, thus considering fibre cables that are aggregated along common routes, i.e. sharing common ducts located along the streets.

6.2.2.1 Initialisation

The algorithm in Fig. 6.4 attempts to obtain an initial solution by partitioning end-users so that the number of collisions among clusters is minimised. If a collision between a pair of clusters exists,

```
function INITIALISE($G, U, C\_SIZE$)
    $g \leftarrow getVertex(G)$                                  ▷ $g \in V$, e.g., gravity centre
    $dist_v \leftarrow Dijkstra(G, g), v \in V$
    $P = \emptyset$
    for $v \in U$ do
        $P.add(pair(v, dist_v))$
    end for
    $SortDescending(P)$
    while $P.notEmpty()$ do
        $p = POP\_FURTHEST(P)$
        $C \leftarrow Dijkstra(G, p.v, C\_SIZE)$              ▷ get $C\_SIZE$ nearest neighbours
        $clust.centre \leftarrow findCentre(C)$
        $clust.members \leftarrow p.v$
        $Clusts.add(clust)$
        for $u \in C$ do
            $P.remove(u)$
        end for
    end while
    return $Clusts$
end function
```

Figure 6.4: The initialisation step: get a promising solution reducing the number of collisions between clusters.

it means that clusters overlap and share a common street segment. A collision may indicate a non-optimal solution and hence, re-connections are required between a pair of affected clusters to improve the solution.

6.2.2.2 Enhancement

The algorithm in Fig. 6.5 improves the solution by performing a series of re-connections among clusters. A re-connection is carried out by swapping a pair of end-users between a pair of clusters, which leads to improvements in the objective function.

Based on experiments, two different types of clustering were considered, described in next Section 6.2.3. The algorithm operates until no further improvement is found, i.e., there exists no re-connection that improves the solution.

6.2.3 The heuristic

The heuristic implements a complex variant of a general problem known as Capacitated Clustering Problem (CCP) [94]. The main goal of the heuristic is to provide a valid multi-stage ODN and optimise CAPEX (defined in Section 6.3). To fulfil the aim, the single-stage clustering from the previous subsection 6.2.2 is combined to build a multi-stage, i.e. hierarchical, clustering algorithm. Subsequent calls of the single-stage algorithm (in Section 6.2.2) yield hierarchical clusters. For example, for CM 16x4x2 which involves three optical splitter stages, the single-stage algorithm runs three times, i.e. one time for each stage. Each call sets the parameter C_SIZE in Fig. 6.4 to the splitter size at corresponding stage, e.g. for CM 16x4x2 the parameter is first set to 16, then to 4 in the next call, and to 2 in the

```
function Improve($G, C$)
    $improvement \leftarrow false$
    $O \leftarrow pairsOfClustersThatOverlap(C)$
    repeat
        $improvement \leftarrow false$
        for $(c1, c2) \in O$ do
            $U_1 \leftarrow verticesThatCauseOverlapping(c1, c2)$
            $U_2 \leftarrow verticesThatCauseOverlapping(c2, c1)$
            if $size(U_2) \leq size(U_1)$ then
                $U_1 \leftarrow U_2$
            end if
            $initV \leftarrow minV \leftarrow calcObjVal(c1, c2)$
            for $u1 \in U_1$ do
                for $u2 \in c2.members$ do
                    $swap(c1, c2, u1, u2)$
                    $newV \leftarrow calcObjVal(c1, c2)$
                    $swap(c1, c2, u2, u1)$                                ▷ swap back
                    if $newV < minV$ then
                        $minV = newV$
                        $bestV1 = u1$
                        $bestV2 = u2$
                    end if
                end for
            end for
            if $minV < initV$ then
                $swap(c1, c2, bestV1, bestV2)$
                $improvement \leftarrow true$
                $Update(O, c1, c2)$
            end if
        end for
    until $improvemnt = true$
end function
```

Figure 6.5: Improvement step: reconnect end-users among clusters as long as objective function can be improved.

last call. Moreover, due to prior assessment showing that particular algorithms are more suitable for the goals described below, the heuristic mixes two different types of clustering algorithms:

a) *P-median* [95] - minimises the total length of (fibre) connections formed between the cluster centre (e.g. a drop point) and cluster members (e.g. end users). In other words, the objective of *P-median* is to position the centre of a cluster towards the most dense region. Fig. 6.6 illustrates how the objective function (*obj1*) of *P-median* clustering achieves its optimum;

b) *min-max* [96] - a clustering that minimises the maximum distance to the cluster centre. Fig. 6.6 illustrates how the objective function (*obj2*) of *min-max* clustering achieves its optimum.

The target for both the methods is to leverage the trade-off between the cost of ODN deployment and the number of PONs required, both contributing to the overall network cost that is the aim of minimisation. More specifically, the former clustering approach attempts to minimise the ODN cost, while the latter method leads indirectly to minimised number of PONs and thus the number of OLT cards. P-median and min-max clustering algorithms have different objective functions, and therefore,

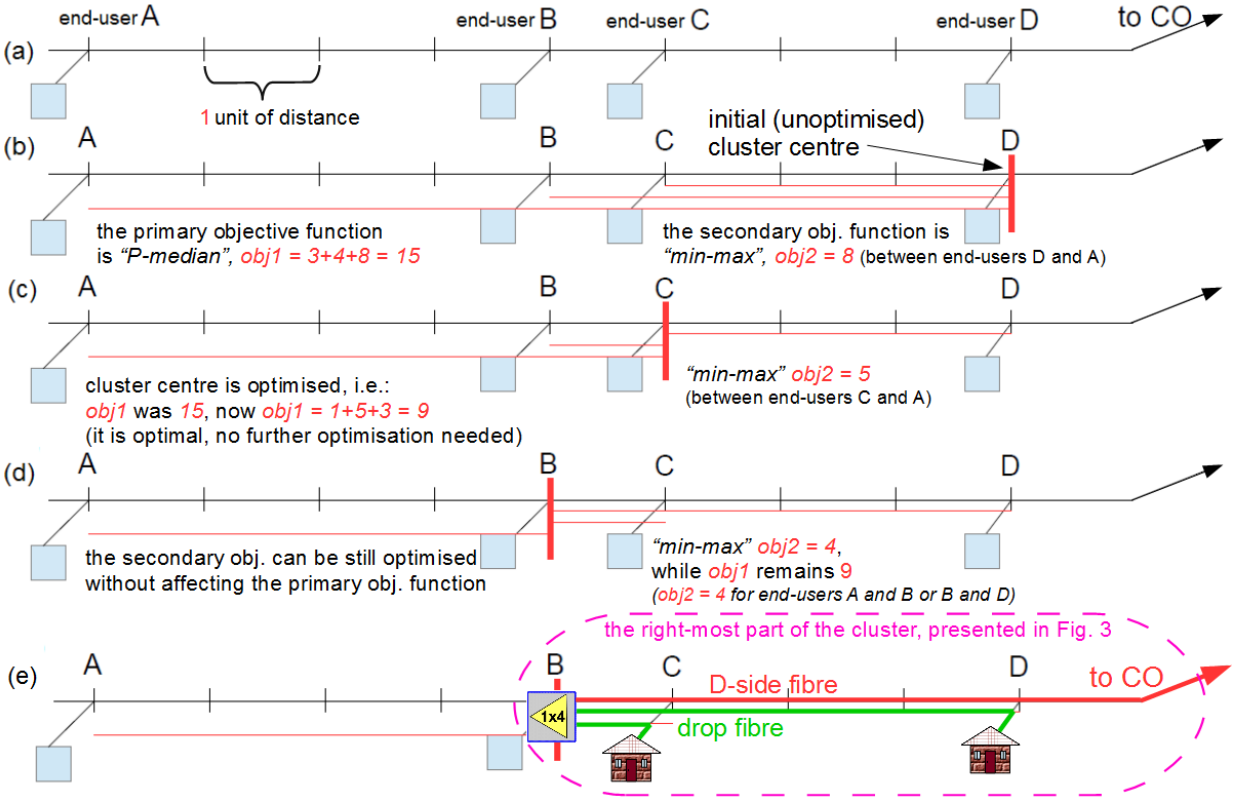


Figure 6.6: House-connecting stage clustering with *P-median* as the primary objective function and *min-max* as the secondary objective function. P-median optimises the amount of fibre used, i.e. its total length which is calculated in Figure (b) as a sum of distances between end-users and the cluster centre. Namely, $obj1 = len(D, C) + len(D, B) + len(D, A) = 3 + 4 + 8 = 15$. Then, in Figure (c), the optimisation is performed by changing the cluster centre from D to C, resulting in a lower value of $obj1$. Next, min-max minimises the maximum distance between end-users and the cluster centre, e.g., in Figure (c), $obj2 = max(len(C, D), len(C, B), len(C, A)) = max(3, 1, 5) = 5$. By changing the cluster centre from C to D in Figure (d), $obj2$ is minimised. Figure (e) illustrates a situation where end-users C and D take up the service and get connected to FTTH network, while end-user A does not take up the service.

those methods were employed as alternative primary objective functions, i.e. each method at a suitable stage in the ODN. The suitability between P-median or min-max method to different stages was found experimentally. The former one is employed at the last stage (both $findCentre(C)$ in Fig. 6.4 and $calcObjVal(c1, c2)$ in Fig. 6.5 employ P-median as the primary objective function), since this is more appropriate to the house-connecting stage. At this stage, min-max method is also employed as the secondary objective function. The secondary objective function optimises a solution without deteriorating the primary objective function as illustrated in Fig. 6.6. The other stages focus on optimising the number of ODN branches (and thus the number of PONs) as this is more important in the house-passing stages. So in other stages, both $findCentre(C)$ in Fig. 6.4 and $calcObjVal(c1, c2)$ in Fig. 6.5 employ min-max as the primary objective function.

Moreover, the heuristic includes: a) support for variable PON length and split, and b) using small optical splitters in lower stages of the ODN tree. In order to serve the most remote rural areas, the heuristic trades between ODN reach and split size. For example, when the maximum reach constraint is violated while forming a 128-size cluster (i.e., 10 km for 128 ODN [13]), the heuristic reduces the ODN branch size while ensuring the correct power budget. The remaining end-users need to be served by different ODN branches, or by a different PON tree altogether. The process reduces the overall number of end-users served by a single ODN branch by a factor of two, trading a longer overall reach for a lower number of end-users served by an OLT card.

In addition, the use of smaller splitters at lower stages, i.e., using *16x4x2* instead of *16x8* helps to optimise the number of ODN branches, due to higher flexibility in positioning the splitters. In addition, it provides the flexibility to deploy ODN branches on demand.

6.3 Cost model and pricing scheme

In order to obtain the final cost figures, the results from the heuristic must be additionally processed, i.e. the individual fibres aggregated into cables and ducts, and finally, the pricing scheme can be applied to this raw data.

This section briefly describes the assumptions for cost modelling for rural network deployment, used to compare a number of different deployment strategies. Items whose cost does not depend on such strategy are omitted from the model, e.g., the cost of ONUs. The pricing scheme was derived from vendors and operators within the European DISCUS project. Examples of comparable cost figures were provided in [97]. A sensitivity analysis is given in Section 6.4.6.4.3, so that the results can be analysed against variation in some of the key costs.

6.3.1 Ducting

The construction cost of ducting infrastructure varies significantly and depends on many factors. Trenching is one of the most expensive techniques. According to [28], civil work for digging trenches accounts for up to 80%-90% of total FTTH investment in a rural Danish scenario. This creates strong motivation to consider more cost-effective alternatives, such as aerial ducting. Similar to the Danish scenario, but also occurring in other countries [98], the strategy assumes that the electric utility companies may participate in fibre network deployment. For this reason, in addition to the fact that telecommunications providers typically own aerial infrastructure in rural areas to deliver their current phone/DSL offers, the model devised in this chapter omits the capital poles construction cost and considers only the aerial ducting installation cost over existing poles. The cost of aerial fibre network construction may vary considerably in different deployment scenarios [99], [100], [101], [41].

The solution considered here for ducting is blown fibre tube (BFT), employed in a real-world FTTH roll-out by European operators [63]. A BFT is a plastic tube consisting of a number of smaller subtubes. Since, a cost-effective deployment is the target, a wide range of BFT sizes is considered to address

Table 6.2: PRICING SCHEME AND DEPLOYMENT PLANNING DETAILS

	Capacity or rate	Costs	Planning details
Ducting (C1)	T_1 set contains 1-BFT, 2-BFT, 4-BFT, 7-BFT, 9-BFT, 12-BFT, 19-BFT	C_t^1 set contains 180, 310, 520, 800, 970, 1200, 1750 (EUR/km) where $t \in T_1$	C_t^1 includes the cost of materials. The planning is fully automated by the heuristic (in Section 6.2) which dimensions the size of duct links planned along the streets according to required fibre capacity and particular deployment scenario (Fig. 6.1). So, it is known in advance what variant of BFT to install in both stages in Fig. 6.1.
Splitter and splice nodes (C2)	T_2 set contains 2, 4, 8, 16, 32	C_t^2 set contains 290, 340, 440, 620, 990 (EUR/node) where $t \in T_2$	Splitter/splice nodes must be installed on the poles (the positions where install the nodes are provided by the heuristic in Section 6.2) to interconnect the ducts. C_t^2 set contains both material and labour costs, and BoM (Bill of Materials) is illustrated in Fig. 6.7. The total cost of a node also includes the labour cost required to install a node on a pole, which is set to 1 hour for two workers.
Blown fiber cabling (C3)	T_3 set contains 4-BFU, 8-BFU, 12-BFU	C_t^3 set contains 130, 240, 330 (EUR/km) where $t \in T_3$	C_t^3 contains both material and labour costs. The labour is required to blow fibre into the infrastructure of ducts.
Duct installation (C4)	T_4 set contains 1h/km, 4h/km	C_t^4 set contains 210, 840 (EUR/km) where $t \in T_4$	C_t^4 includes the labour cost required to install a kilometre of duct over poles with rate $t \in T_4$. The planning is fully automated by the heuristic (in Section 6.2) which creates a duct installation schedule. It is known in advance when a particular duct (in row C1) should be installed. The schedule differs between the methods in Fig. 6.1.

varying density in rural population. While smaller BFTs (e.g., 1-BFT) are highly suitable for sparser areas, larger BFTs (e.g., 7-BFT) are designated for denser areas. BFT sizes and pricing are summarised in Table 6.2 in row C1 and were derived from operators data.

The cost of duct installation (i.e., labour) is investigated in Table 6.2 in row C4 separately, as it can vary considerably. Practical deployment sources [66] show the possibility to carry out duct installations at the rate of 4 hours per kilometre, for a two-worker team. The examination also takes into account faster rates, i.e., 2.5 and 1 hours per kilometre. In fact, installing ducting with a rate near to 1 hour per kilometre is also reported in [66] as the best practice rate for ploughing technique in rural Denmark. Another low-cost alternative is the micro-trenching technique, which is considered for example as an option for covering rural Norway [40]. Since the fibre network deployment techniques constantly improve, there may be expected further improvement in installation time.

The planning of duct deployment progresses as follows. An infrastructure of poles is in place (this is an assumption). End users must be passed first, i.e. the ducts over poles must be installed (this involves both C1 and C4). Once end-user demands the service, an onsite visit is required. This typically involves the duct installation (both C1 and C4) between the splitter and end-user's street access point as shown in Stage II in Fig. 6.1. Onsite visit also involves the construction work to deliver the link between the

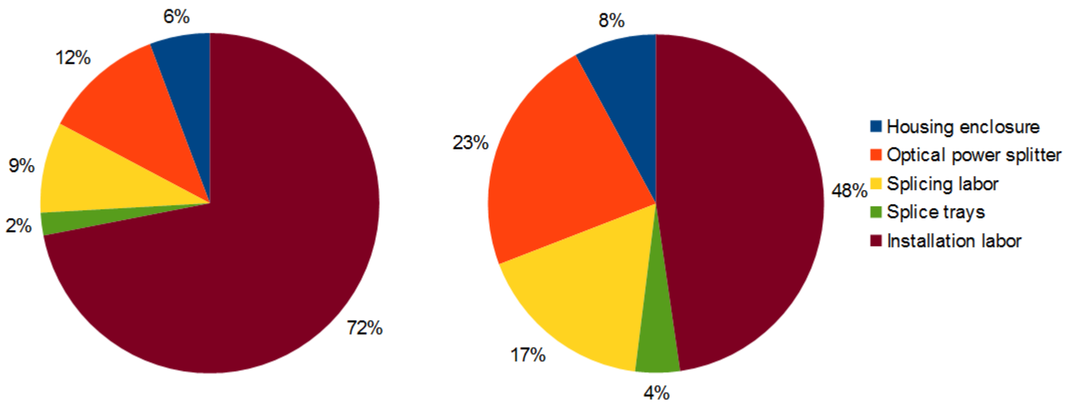


Figure 6.7: Sample 2-size (on the left) and 8-size (on the right) splitter/splice nodes, and their composite cost share.

end-user's home and the closest street. The cost of this link is taken into account below in NPV analysis in S_{avg} cost in Section 6.5 because the cost is not relevant when comparing the connection methods in Fig. 6.9.

6.3.2 Splitter/splice nodes

A splitter/splice node is an enclosure designated for optical power splitters installation and fibre splicing. Multiple node variants are considered to serve cost-effective deployment both in sparser and denser rural areas. Splitter sizes and pricing are summarised in Table 6.2. The total cost of a single node in Table 6.2 includes: housing enclosure, optical power splitter, splice trays, splicing and installation labour. Fig. 6.7 shows two variants, i.e. 2-size and 8-size, splitter/splice nodes and their components cost share.

6.3.3 Blown fibre (cabling)

Once a duct network and splitter/splice nodes are in place, blowing the fibres into the ducts can be initiated. A Blown Fibre Unit (BFU) is considered for this purpose [63], a technology that encapsulates a number of fibres into a single BFU. While small 4-BFU can be used for drop connection, larger fibre units, e.g., 12-BFU, help to reduce the deployment cost by aggregating the fibres passing through common routes. BFU sizes and pricing are also summarised in Table 6.2.

6.4 Results and techno-economic analysis

In this section, the three different deployment solutions described in Section 6.1 were implemented. The goal is to compare their applicability to different scenarios and to identify what types of costs affect the deployment more in sparsely populated areas. Variable parameters that are considered: take-up rate, deployment model and splitter configuration. The CM1 strategy, intended for low-risk scenarios, is adopted as the baseline in the comparison.

In Section 6.4.4, an attempt is made to devise a methodology designated for variable take-up rate analysis. In other words, a simulation was performed, by connecting end-users one-by-one to the network via a ”long drop” connection and plot a subsequent total deployment cost. The variation in the cost value depends on the order in which particular users join the network. The aim here is to estimate, for all methods in Section 6.1, the extent of that cost fluctuation. As it was already mentioned above, operators may be more interested in rural roll-out if they know the risk associated with particular take-up rate values. Moreover, the special interest is devoted to estimating a hypothetical average deployment cost for each method. Having such an average estimation, a sensible comparison in Section 6.4.5 can be made. Also, additional interest is devoted to showing cost figures for various duct installation speeds. This enables a discussion on whether a research on faster deployment techniques is worth considering.

6.4.1 The baseline connection method for low-risk scenarios (CM1)

First, the total deployment cost for a low-risk service take-up scenario is examined, where the maximum user uptake is assumed, in order to provide a lower bound reference point for the comparison. Fig. 6.8 reports the deployment cost, calculated for rural Ireland use case shown in Fig. 6.2. In the x axis, the splitter configurations are arranged in descending order with respect to the last stage splitter size.

An emerging trend can be seen: the cabling component cost decreases, whereas the node-related component cost increases; overall, the total deployment cost tend to decrease. The decrease stems from: redistributing the optical splitters more evenly, especially in the third stage (an approach that is the opposite of that used in urban areas). Aggregating single fibres into multi-fibre units (shown with a plus sign) also produces some minor improvements. An exception to the trend appears for configuration *4x16x2+* where a higher number of nodes has to be used in the drop section, because the second stage splitter has doubled the number of ports (i.e., 16 vs. 8), making *4x16x2+* slightly worse as compared to *8x8x2+*. In fact, it can be seen that here it is the node cost that is relatively high, as this is proportional to the number of splitter nodes required, and it is nearly two times higher for *4x16x2+* compared to *8x8x2+*.

6.4.2 Passing, drop, and total costs trade-off

In order to account for variable take-up rates, first, there is a need to separate the passing and the drop costs from the total cost. The passing cost accounts for network set-up between a local exchange and drop points, whereas the drop cost relates to all ”long drop” links to end-users set-up costs.

Typically, when a high uptake is expected, there is no need to trade off passing cost against drop cost. However, when take-up rate growth is uncertain, understanding this trade-off becomes essential.

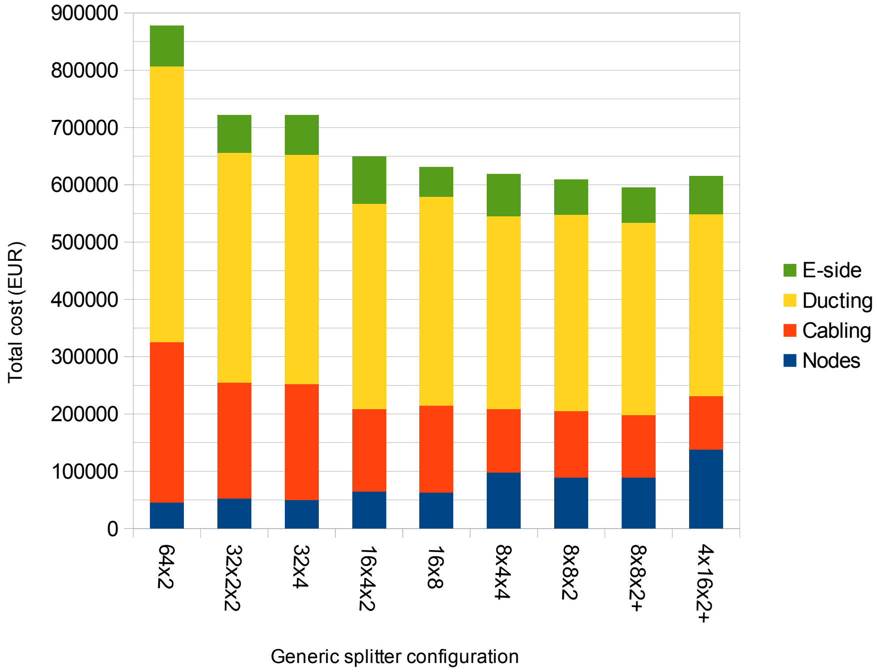


Figure 6.8: Total deployment cost for different splitter configurations available within default connection method CM1, all end-users are connected (100% take-up rate).

Examining such trade-off for the different connection methods, Fig. 6.9 reveals compelling dissimilarities in the network cost. Interestingly, when comparing *CM1: 4x16x2+* and *CM3: 16x4x2* total costs, one might believe that the former option is a better one, since it is 25% lower. However, the latter option exhibits a significantly lower (about 50%) initial, up-front deployment cost (the passing cost). Hence, the latter option might be worth considering for high-risk take-up areas, for example in a situation with slow expected network growth.

The value of total cost shown in Fig. 6.9 is calculated as follows:

$$\begin{aligned} t_c = \sum_{t\in T_1} C^1_t \cdot duct^{len}_t + \sum_{t\in T_2} C^2_t \cdot node^{count}_t + \\ \sum_{t\in T_3} C^3_t \cdot fibre^{len}_t + \sum_{t\in T_1} C^4_r \cdot duct^{len}_t \end{aligned} \tag{6.1}$$

, where:

- t_c - the total deployment cost shown in Fig. 6.9;
- $duct^{len}_t$ - the length of duct of particular type $t \in T_1$ required in a deployment. This value is yielded by the heuristic in Section 6.2;
- $node^{count}_t$ - the number of splitter/splice nodes of particular type $t \in T_2$ required in a deployment. This value is yielded by the heuristic in Section 6.2;

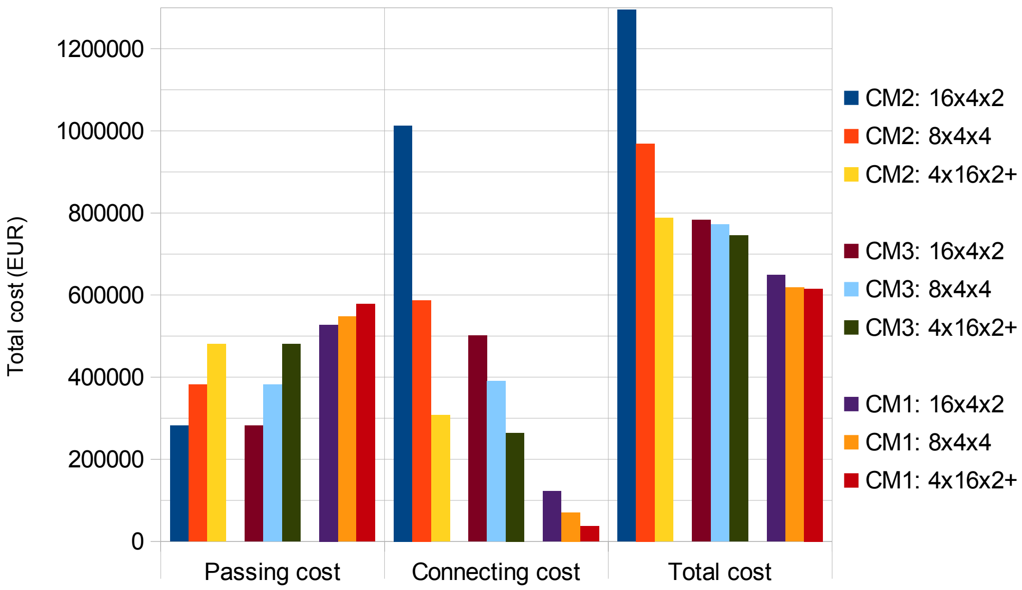


Figure 6.9: Passing and drop costs for different connection methods, all end-users are connected (take-up rate is 100%). Total cost is equal to t_c in Equation 6.1.

- $fibre_t^{len}$ - the length of fibre cable of particular type $t \in T_3$. This value is yielded by the heuristic in Section 6.2;
- r - duct installation rate, $r \in T_4$, which is constant in a single experiment (deployment).

6.4.3 Sensitivity analysis

A sensitivity study of the parameters in Table 6.2 was performed and shown in Table 6.3 and Fig. 6.10. The figure and table measure the sensitivity of the total cost (Fig. 6.9) under the assumption of 10% increase in a component cost. For example, the result for option *CM2: 16x4x2* illustrates that by increasing the cost of blown fibre (C_t^3) in Equation 6.1 by 10% (i.e. the cost of 4-BFU increases to $130 * 110\%$ EUR/km, the cost of 8-BFU increases to $240 * 110\%$ EUR/km, and so forth), the total cost of deployment increases by 1.19%. On the other hand, 10% increase to the duct installation cost incurs 6.78% increase in the total cost. In other words, it indicates that the total cost is more sensitive (a few times) to the variation of duct installation cost, in the case of option *CM2: 16x4x2*.

The sensitivity of total cost is different between the connection methods. For example, the sensitivity for duct installation cost is different for CM2 and CM1. Namely, CM1 guarantees a lower sensitivity because this method tends to minimise the total length of ducting (by employing duct sharing methodology as shown in Fig. 6.1). In effect, CM1 involves less ducting, and therefore, it is less subjected to an increase (or decrease) in the total cost.

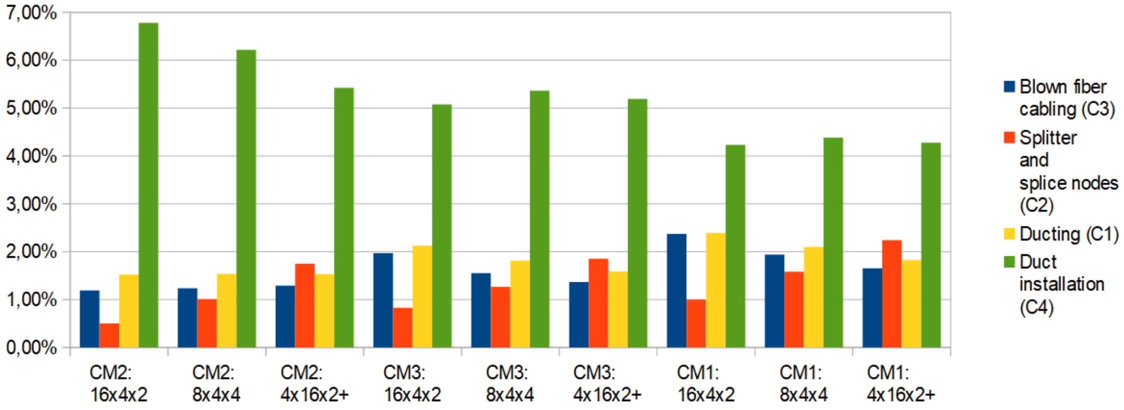


Figure 6.10: Sensitivity analysis of component costs as a result of 10% increase (or decrease) in total deployment cost (t_c).

	All component costs of the total deployment cost (t_c) in Equation 6.1			
	Blown fibre cabling (C3)	Splitter and splice nodes (C2)	Ducting (C1)	Duct installation (C4)
CM2: 16x4x2	1,19%	0,50%	1,52%	6,78%
CM2: 8x4x4	1,24%	1,01%	1,54%	6,22%
CM2: 4x16x2+	1,29%	1,75%	1,53%	5,42%
CM3: 16x4x2	1,97%	0,83%	2,12%	5,08%
CM3: 8x4x4	1,55%	1,27%	1,82%	5,37%
CM3: 4x16x2+	1,37%	1,85%	1,59%	5,19%
CM1: 16x4x2	2,37%	1,00%	2,39%	4,23%
CM1: 8x4x4	1,94%	1,58%	2,10%	4,38%
CM1: 4x16x2+	1,66%	2,24%	1,82%	4,28%

Table 6.3: Sensitivity analysis of the total deployment cost (t_c) caused by 10% increase (or decrease) in all component costs illustrated as percentage share.

6.4.4 Measuring the effect of fluctuations in users take-up

This section analyses how the order in which customers might join the network can affect the cost for the operator. In this case, the passing cost is fixed, as the users' take-up pattern only affects the connecting cost at the drop. In order to highlight the relevance of the customer take-up order on cost variation, best and worst-case cost curves were plotted, which provide a lower and upper cost boundaries for all other possible outcomes. The following types of curves were distinguished:

- Best-case cost curve: end-users that incur the lowest drop cost join first. A greedy algorithm to generate this type of curve was formulated and employed;
- Worst-case cost curve – a reverse to best-case curve, i.e., end-users that generate the highest drop cost join first. Again, a greedy approach to compute this curve was formulated and employed;
- Random cost curve – reflects the cost incurred when users request FTTH connectivity in random

order;

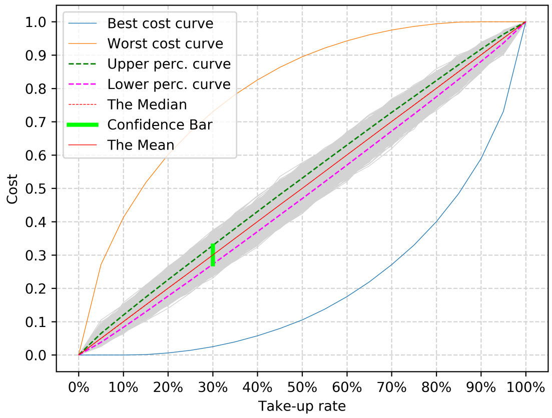
- Average randomised cost curve – an average over multiple random orderings, i.e., multiple random cost curves. The mean is used to anticipate the common cost curve for all end-users, expected on average. In Fig. 6.11, the mean is calculated over 10^5 random curves;
- The upper and lower percentile curves, in Fig. 6.11, indicate the area where 90% of all random curves (i.e. 10^5) is enclosed for every value of take-up rate. In other words, the curves indicate 5th and 95th percentiles.

Sample curves are illustrated for all connection methods of *CM: 8x4x4* in Fig. 6.11. The best-case curve graph depicts ordering where the expenditures for increasing subscription can be minimised especially when the percentage of subscribers is low. Indeed, Fig. 6.11 indicates relatively low additional cost to reach 30% take-up (the meaning of this threshold is explained later). The area between the two curves (best and worst) is a measure of the uncertainty of the rural FTTH deployment cost, due to this users' take-up effect. However, in a real-world scenario, end-users typically join the network randomly. Therefore, a notion of an approximated curve was embraced to estimate a random ordering. A realistic approximation results from averaging a large number (10^5) of random cost curves – a grey area in Fig. 6.11. The experiments involving a different number of random curves were carried out up to a practicable value, i.e. 10^5, in order to illustrate that their number (once above 5,000) has little effect on the confidence bar.

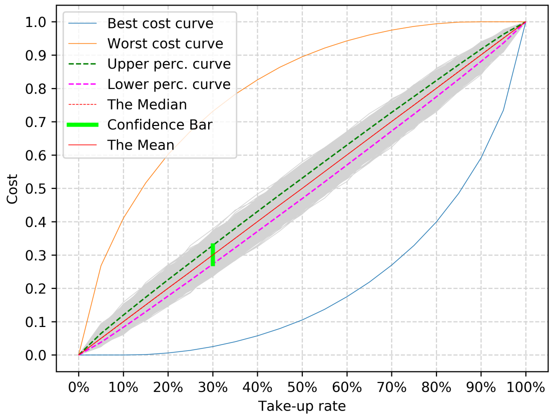
In Fig. 6.12, this analysis is extended to all deployment methods and splitter configurations. Namely, the evaluation in Fig. 6.11 indicates that most of the predictions out of 10^5, i.e. 90% of the random curves, concentrates around the mean, i.e. between percentile curves, and none of the predictions appears in close proximity to best-case and worst-case scenarios. Also, a hypothetical threshold was defined, i.e. at least 30% uptake must be reached for viable network operation (marked with a blue dashed line), similarly to [102].

In Fig. 6.12, the size of the area enclosed by these two curves is proportional to the uncertainty in deployment cost associated to a specific strategy, with respect to uptake rate, as illustrated in Fig. 6.11 and Fig. 6.13. The method *CM1* is most stable in terms of cost fluctuation with respect to customers joining in different order, when compared to other methods, as the curves subtend the smallest area. On the other hand, *CM2* and *CM3* bear far higher cost variability and uncertainty. In fact, the option *CM2: 16x4x2* represents the worst case, where the cost can fluctuate over a wide range between about 350k and 950k EUR at 30% take-up point as shown in Fig. 6.13.

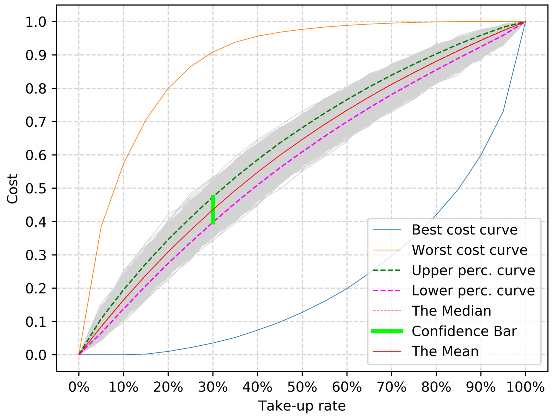
As mentioned above, for higher-risk rural scenarios, it is important to keep the initial cost low. For this reason, in this chapter, cost figures that are around 30% take-up rate and below are examined, as the rural scenario is high-risk, and it is important to analyse its viability at lower take-up values. Even if commercial operators might not have a viable business case, it is important for other players



(a) CM1



(b) CM2



(c) CM3

Figure 6.11: The confidence region estimation. The region is defined by the confidence bar that denotes 90% percentile of random curves, i.e. between upper and lower percentile curves (at 30% take-up rate). The green area reflects all random curves.

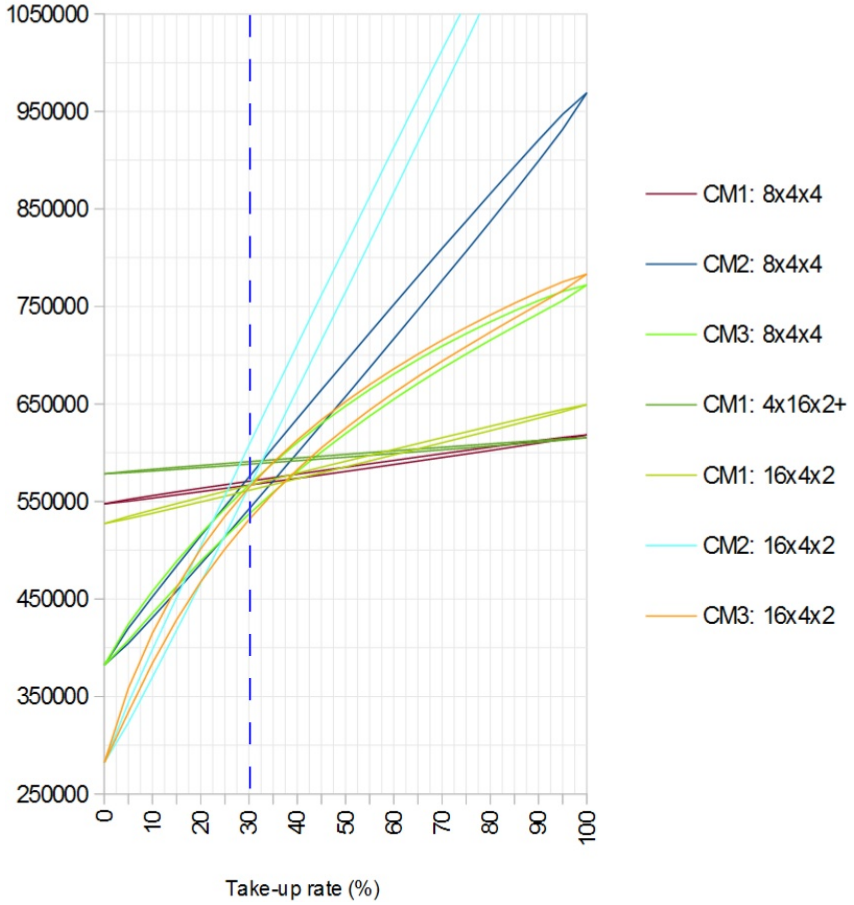


Figure 6.12: Cost uncertainty area enclosed between upper and lower percentile curves for all connection methods.

(e.g., municipalities or central governments) to understand the trade-off between different strategies. In Fig. 6.13, option CM3: 16x4x2 guarantees the lowest deployment cost at 30% take-up rate (best-case cost curve). Fig. 6.12 and Fig. 6.13 show together a clear trade-off between low upfront cost and low uncertainty, which needs to be evaluated attentively by the operator, there are cases where there is an obvious winner. For example CM3:16x4x2 has lower uncertainty and lower cost than CM2: 16x4x2.

One question that can be asked, is what are the mean expectations considering users joining in random orders. To clarify this point, in Fig. 6.13, a similar analysis is reported but visualised in terms of average values and their statistical deviation. Here, the mean value (calculated over 10^5 instances) is denoted by the red horizontal marker in Fig. 6.13. Random curves deviate up or down from the average cost. To indicate where the random curves are expected to occur more frequently (between 5th and 95th percentiles), confidence bars are used and denoted by the green segments. Thus, it can be seen that in principle different strategy can have considerable difference in cost, depending on how the users join the network. If one focuses however on the confidence bars, the difference tends to decrease, as all options show costs between around 500k and 600k EUR for a 30% uptake (Fig. 6.13). The next section brings an additional, highly relevant, perspective into the discussion: the cost per customer connected.

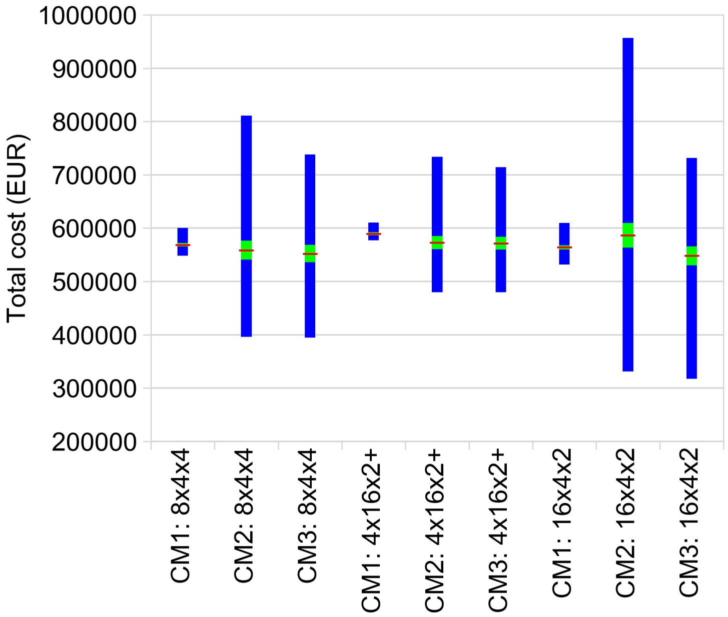


Figure 6.13: Cost error bars at 30% uptake: a) average cost – the mean (red marker), b) confidence bar (green segment), c) potential deviation towards worst-case and best-case curves (blue segment).

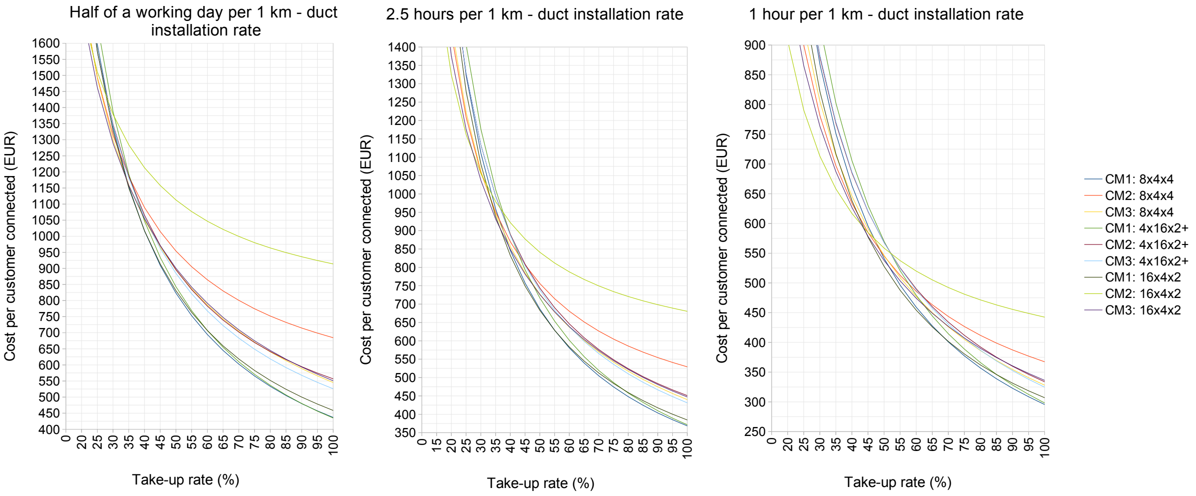


Figure 6.14: Cost per customer connected curves for different duct installation rates.

6.4.5 Cost per customer connected

The next parameter under analyse is the cost per customer connected (CPCC). CPCC is a foundation for complex business models and helps to estimate, for instance, fees for customers, investment pay-back time, or how many customers need to join the network before it becomes financially viable.

Graphs in Fig. 6.14 compare CPCC for all methods, also considering different duct installation rates (DIRs). Generally, a lower *CPCC* should encourage a higher number of customers to subscribe to the fibre-based services. The cost figures are relatively lower compared to the cost of 1500 EUR/customer installation fee proposed for rural Swedish scenario [92], although here a direct comparison is not possible since the study in this chapter assumes existing electric post infrastructure and excludes ONUs cost.

Interestingly, Fig. 6.14 reveals a diversified performance for the different connection and splitter combinations at different take-up rates. In fact, some of the combinations outperform the others up to a pivot point. Thereafter, the performance of those combinations degrade. This can be noticed in the plot that assumes 1 hour per km duct installation rate. Options *CM3: 16x4x2*, *CM2: 8x4x4* and *CM2: 16x4x2* outperform the other combinations up to a 45% take-up rate. However, after 45% take-up rate, their performance deteriorates as compared to the other combinations. The reason can be explored in Fig. 6.1. Options such as *CM3* and *CM2* are designed to minimise up-front expenditure, which however incurs a relatively higher costs later. By limiting duct sharing in *CM3* or *CM2*, there is additional labour cost incurred in the installation of new drop ducts, as shown in Fig. 6.1.

These combinations might be worth considering in the areas where a low take-up is expected. However, gradual increase in penetration is rather inevitable and therefore, these particular combinations might not be adequate in the long run. In fact, options *CM2: 16x4x2* and *CM2: 8x4x4* show significantly lower performance for take-up rates nearing 100% – most apparent for half a day per km DIR. Low performance is caused by CM2 and large size splitters in the drop section, i.e., *1x8* and *1x16.* On the contrary, option *CM2: 4x16x2+* uses small splitters, i.e., *1x4*, and does not get affected with the changing take-up rates. The three graphs quantify how significantly a lower DIR can reduce connecting costs. It also shows, as it could be expected, that a lower DIR compresses the costs of the different methods, reducing their difference.

Overall, this trade-off needs to be considered with respect to the time for return on investment. Thus, although the take-up rate might grow slowly over time, the decision over which deployment strategy to implement will depend on the take-up rate that can be achieved within a given target time-frame.

6.4.6 Discussion

This section provides an overall summary of the findings described in the previous sections. Firstly, the methodology aimed at demonstrating by how much deployment cost can vary, depending on deployment strategy. This was expressed in terms of both splitter configurations and expected take up rate. Secondly, it was showed for a specific use case, based on realistic data (i.e., end user locations and street maps), which splitter configuration proved most effective. The CM1 method shows the highest cost performance, where the operator can expect with reasonable certainty to achieve a high service uptake. However, whenever uncertainty or expectation of low uptake prevails, either the CM2 or CM3 methods seem preferable, as they reduce the risk of investment. This is because both options offer lower up-front cost required to pass end-users compared to option CM1.

As demonstrated above, among those options, CM3 presents a lower cost variance with take-up. Finally, it was showed that the specific 16x4x2 splitter configuration, applied to CM3, shows the highest cost performance for low take-up rates, for the specific scenario considered. The next section completes the analysis, by reporting the net present value calculation for the preferred option.

6.5 Net present value and payback period

In this section, net present value (NPV) was calculated, in order to estimate the time required before the network becomes profitable (i.e., the value of NPV becomes positive). The value of NPV can be calculated as follows:

$$NPV = \sum_{t=0}^{t} \frac{C_t}{(1+r)^t} - I_0 + N * F$$

The following symbols denote:

- t is the time considered in years (the maximum value assumed is 40 years). This is in line with other studies such as [4] in Sweden;
- r is the discount rate: examination assumes 3%;
- S_{avg} is the average cost of connecting a single end-user. This cost includes: (a) ONU cost, (b) cost of onsite visit, (c) cost of constructing fibre connection between the home and the fibre network in the closest road. Assumption is that S_{avg} equals 2,000 EUR in Table 6.4. For instance, [4] considers 1500 EUR/customer installation fee which is intended to compensate for S_{avg} expenditure. Real value of S_{avg} heavily depends on the cost of the link (between the home and the fibre network in the closest road) construction, which varies depending on deployment technique (e.g. underground, overhead) used, the distance of house to the closest street, the amount of manual digging involved, etc. In Table 6.5, additional results for S_{avg} values of 1,000 and 4,000 EUR are reported;
- N_t is the total number of end-users (i.e. 1416) in the area under investigation;
- N is the number of end-users connected;
- I_0 is the initial deployment expenditure. This cost includes: (a) the cost of the network deployment (100% end-users passed and N end-users connected); (b) $S_{avg} * N$: the total cost of connecting end-users; (c) the cost of amplifier nodes;
- P is the monthly profit coming from a single end-user; the profit is equal to: the revenue minus operational expenses (OPEX). Due to the difficulty in providing correct values, OPEX and revenue values are not explicitly considered but through the simpler profit as a variable. The value of profit can be higher than in Table 6.4 depending on the monthly fee (which is set by an operator) and the operational cost (which becomes known when the network operates). The order of this value is expected to range in dozens of EUR, e.g. a monthly fee set by an operator can be 50

EUR/month, avg. operational cost can be 20 EUR/month, and then P is equal to 50 EUR/month - 20 EUR/month = 30 EUR/month (per customer). In Tab. 6.5, the minimum profit value that operators should assure in order to reach a viable payback time is reported;

- F is the value of one-time installation fee per end-user;
- C_t is the total yearly profit from all end-users, assumed to be constant and equal to $P * N * 12$.

Table 6.4 estimates the payback time for connection method *CM3: 16x4x2* depending on the values of P (monthly profit per end-user), F (one-time installation fee per end-user), and take-up rate (N). Higher values of take-up, P, and F help to decrease the payback time, i.e., shorten the time required to reach a positive NPV. The values show, for example, how the proposed strategy can achieve a payback time of 7 years even for a low take up rate of 25%. However, this would require an end-user contribution of 1,500 EUR for a 7 year payback period or 500 EUR for 12 years. It should be noticed that both time frames are likely to be too high for a commercial operator, but might be reasonable where the government might subsidise part of the cost.

Moreover, Table 6.5 is provided to include a number of additional scenarios which result from different S_{avg} and P values.

N	P (EUR)	F (EUR)	Payback period (years) (NPV value becomes positive, after that period)
$N_t \cdot 5\%$	10	0	never within 40 year period
		500	never within 40 year period
		1500	never within 40 year period
	20	0	33
		500	28
		1500	19
$N_t \cdot 25\%$	10	0	never within 40 year period
		500	31
		1500	15
	20	0	16
		500	12
		1500	7
$N_t \cdot 75\%$	10	0	32
		500	23
		1500	10
	20	0	13
		500	10
		1500	5

Table 6.4: Payback time for *CM3: 16x4x2* (the random end-users connection order, duct installation rate: 1km/1h)

6.6 Conclusion

In this chapter, a number of different FTTH deployment strategies was examined for rural areas. This work highlighted how deployments in rural scenarios affect not only the overall economic viability, as

			Payback period (years) (NPV value becomes positive, after that period)	
	P (EUR)	F (EUR)	S_{avg}=1000 (EUR)	S_{avg}=4000 (EUR)
	10	0	90	x
		500	56	x
		1500	29	x
	20	0	23	63
		500	19	52
		1500	12	37
	40	0	10	20
		500	9	18
		1500	7	15
	70	0	6	11
		500	6	10
		1500	4	8
minimum profit (P) to obtain viable payback time	10	0	90	x
	9	500	76	x
	6	1500	86	x

Table 6.5: Payback time for *CM3: 16x4x2* for a low take-up scenario ($N = N_t \cdot 5\%$). Marker "x" indicates that deployment is not viable within a 100 years period.

could be expected, but also that different strategies should be used depending on the expected customer take-up rate, in order to reduce the investment risk. The strategies addressed the trade-off between the higher risk upfront cost (i.e., for the initial investment in passing houses) and the lower risk connecting cost (which is lower risk as only carried out once a customer takes up the service).

The investigation of the relationship between cost and service take-up rate led to identification of a significant difference in network cost (per end-user), depending on the expected take up rate. Furthermore, the impact of duct-installation speed on the deployment strategies in terms of economic efficiency was assessed.

The study was evaluated over a specific rural area in the west of Ireland, simulating the effect of different deployment strategies on the upfront and connecting costs, under different scenarios, exemplifying different user take-up rates, installation costs and service charging models.

The findings have illustrated that the specific deployment strategy selected can make a considerable difference on the overall deployment cost and thus in the economic viability. For instance, lower take-up rate can be made profitable by adopting a strategy that favours lower up-front costs at the expense of higher connectivity costs. The decision-making process of investment risk optimisation has led to a specific deployment option (labelled *CM3:16x4x2*) which was employed to show how profitability could be achieved within a 7 year period even for a relatively low take-up rate of 25%.

7 Conclusion

The whole work covers the problem of FTTH roll-out in sparsely populated rural areas. In brief, the work was divided into the following portions. First, the research effort was directed at understanding the problem and its underlying issues. Inevitably, the research entered into a discussion on available technologies and cutting-edge architectures followed by the evaluation of their applicability in the rural scenario. This formed the basis for core investigation. Overall, the quest led to deep insight into rural FTTH deployment economics, thereby helping to identify these circumstances under which the deployment can be commercially viable. This could not occur without application of deployment strategies primarily designed to alleviate and deal with the rural FTTH deployment problem. These methods were mathematically formulated to instantiate a suite of clustering algorithms underpinning and automating the deployment strategies proposed in this work. Further details and contributions of this work are described below.

Introduction opens with background information provided for this work. Namely, it discusses the trends in development of next generation access network technology and compares a number of competitive options, with the recommendation to employ passive optical network (PON) technology, specifically in the access networks in sparsely populated rural areas. Furthermore, the elaboration focused on a more advanced variant of PON, i.e. long-reach PON (LR-PON) technology. This technology is the main topic of this work, and therefore, other comparable solutions were not thoroughly examined. The introduction closes with a problem statement and the motivation to solve it. And lastly, it identifies and explores the key aspects of the problem.

The literature review targeted different localities world-wide so that a number of different ways of tackling the rural FTTH roll-out problem, within different countries, could be highlighted. It also assessed available deployment technologies and deployment techniques, featuring these combinations which can lead to cost-effective adoption of LR-PON technology in the outside rural plant. In addition, the review gathered information about relevant clustering algorithms, thus laying the foundation for the algorithms that were devised in this work.

The whole investigation focused on delivering results that can be used to identify deployment strategies useful in the rural scenario. The rural case was examined in three different scopes, i.e. national (the whole area of Ireland), the area of a single Central Office, and the area of a cabinet.

Because of that, three different groups of models were created to deal with different size of optimisation problems, but in the same time, offer different degree of replication compared with the real-world deployment. The highest degree of replication was provided for the smallest scenario, i.e. within the area of cabinet, whereas the lowest in the national level.

The examination at national level provided a clustering algorithm that yields ODN section of LR-PON network in the country of Ireland in a time-effective way. Different parameters of the algorithm were studied to evaluate what are the most cost-effective configurations of optical power splitters (i.e. their sizes and their arrangement in the ODN topology trees) in the rural areas. In addition, cable sharing was employed to improve final results. The most effective configurations were collected to offer both minimised cable fibre length and maximised utilisation of PONs. It was also shown that cable sharing and branching applied in the close proximity to end users has a significant positive effect and results in the reduction of up to 40% in the total fibre cable length. Also, another multi-criteria clustering algorithm served to partition end-users according to their density and remoteness in order to indicate different geo-types and groups of these end-users, which might require governmental subsidies to get FTTH service.

The investigation in the area of Central Office targeted an in-depth techno-economic examination in rural area. In addition to considering design concepts necessary to accommodate cost-effective sparse (rural) layouts, it considered the dynamic operation of connecting end-users to the network and on-demand network expansion. Another important outcome of this work is the insight on how rural FTTH roll-out economics depends on the take-up rate value. While comparable frameworks proposed increasing the split/fan-out to reduce the upfront cost, an additional methodology to trade off the upfront cost was introduced. For this purpose, three diverse duct sharing methods ("long drop" connection methods) were designated and formulated. In addition, the trade-off of lowering the upfront cost and discussion as to potential risk associated with using a "long drop" connection method were presented.

This portion of work, in the area of rural Central Office, highlighted how deployments in rural scenarios affect not only the overall economic viability, but also that different strategies should be used depending on the expected customer take-up rate, in order to manage and reduce the investment risk. The strategies addressed the trade-off between the higher risk upfront cost (i.e., for the initial investment in passing houses) and the lower risk connecting cost (which is lower risk as only carried out once a customer takes up the service). This investigation of the relationship between cost and service take-up rate led to identification of a significant difference in network cost (per end-user), depending on the expected take-up rate value. Furthermore, the impact of duct-installation speed on the deployment strategies in terms of economic efficiency was assessed. To recap, the evaluation was done over a specific rural area in the west of Ireland, simulating the effect of different deployment strategies on the upfront and connecting costs, under different scenarios, exemplifying different end-user take-up rates, installation costs and service charging models.

The findings of the work above have demonstrated that the specific deployment strategy selected can make a considerable difference on the overall deployment cost and thus in the economic viability. For instance, lower take-up rate can be made profitable by adopting a strategy that favours lower up-front costs at the expense of higher connectivity costs. The decision-making process of investment risk optimisation has led to a specific deployment option, which was employed to show how profitability could be achieved within, e.g., a 7 year period even for a relatively low take-up rate of 25%.

The model for an area covered by a single cabinet is the nearest in its formulation to the real-world deployment. In fact, three different formulations were proposed for rural scenario together with suitable deployment technologies for this type of scenario. It was shown that by employing the formulation with small optical power splitters near the locations of end-users, the size of feeder fibre cable could be reduced, thus significantly improving the initial investment fibre cable cost in excess of 25%. Also, the findings demonstrated a least cost solution because the final solution generally featured 4-fibre cables, i.e. the total cost could not be further reduced as smaller cables (1-fibre or 2-fibre cables) have the same cost as 4-fibre cable.

Overall, this work proved that rural FTTH roll-out case required special consideration, and novel network design strategies were needed to mitigate the problem. This literature is recommended for everyone who can further contribute to the resolution of this problem and Digital Divide problem, including local governments and policy regulators.

7.1 Standardisation and regulations

The standardisation could concern the following aspects relevant to the rural roll-out case:

- the implications of the longer reach of the access part of LR-PON in rural areas, which typically does not occur in the urban case. Aspects such as latency, response time, and lower layer protocols design of PON technology issues (TWDM-PON and WDM-PON) could be specified;
- the extended number of stages of optical power splitters in the access part of LR-PON, which affects, e.g. the attenuation;
- the application of multiple input ports in power optical splitters (protection enabled versus some other benefits, e.g. reduced cost of deployment);
- the application of equal and unequal power optical splitters;
- the recommendations regarding the utilisation of TWDM-PON versus WDM-PON in rural areas;
- the recommendations regarding tree-like versus ring topology in rural areas;
- the drop section of the access part, e.g. its reach depending on the maximum reach of e.g. blown fibre technology;

- the power management schema, e.g. to enable further growth of FTTH network without the need to dimension fibre cables and only dimension the power splitters, which should be a cost-effective strategy.

Rich collection of regulations enforced world-wide is already described in section 2. Essentially, the regulations should be aimed at:

- the involvement (intervention) of the government, local governments or the state;
- legislation of novel deployment technologies to enable cost-effective fibre deployment in the outside plant;
- legislation of novel business cases, which is a broad topic, but can be impactful, e.g. sharing the investment or infrastructure of fibre network among multiple parties;
- the enforcement of fibre technology through green energy programs;
- incentives or tax rebates allowing to adopt fibre technology;
- regulation of fibre lease pricing or fibre market regulations;
- market stimulation towards fibre technology adoption;
- surveys similar to the nationwide census but concerning the FTTH technology prerequisite data;
- the enforcement of a minimum bitrate for wired broadband, which indirectly implies fibre technology;
- national broadband hybrid planning in order to incorporate fibre roll-out in the association with the wireless network roll-out planning.

7.2 Further work

Further work should concern the following topics:

- hybrid approach to the roll-out of fibre network through the intermediate step of wireless network deployment, such as next-generation 5G or 6G networks. In particular, the constraint and trade-offs related to these wireless technologies should be studied and combined with the planning of the FTTH network, specifically in the perspective of a long-term network evolution;
- seamless growth of the fibre network, which can be combined with the study of the topic above.

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