Cost Analysis of Rural Roll-Out using long reach PON: Trading off Upfront Cost Under Uncertainty of User Take-up Rate

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High deployment cost with respect to expected revenue is the main barrier to fibre-to-the-home (FTTH) roll-out in rural areas. This problem, as shown in this paper, is exacerbated by the uncertainty associated to the end user take up rate. The randomness associated with the subscribers service take-up yields considerable fluctuation and escalation in the total cost of deployment. This adverse and varying environment makes it difficult to produce firm business cases and can increase the reluctance of potential investors and incumbent operators to deploy FTTH access networks. In this paper, we develop a holistic framework for examining the real-world FTTH deployment scenarios, taking as case study one of the most rural counties of Ireland. Further, we carry out an in-depth techno-economic analysis identifying the methods more applicable in the rural scenario. We analyse the cost-effectiveness of FTTH deployment, also proposing solutions that provide different levels of upfront investment risk, relating it to uncertainty in customers take-up rates. For example, we show how 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.

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1. INTRODUCTION

Passive optical networks (PONs) have become a key technology for broadband access services owing to its cost-effectiveness and high data rate support. Consequently, PONs have been progressively replacing copper-based networks over the past years as predicted in [1]. The economic benefit of PONs over point-to-point links results from the sharing of the Optical Line Terminal (OLT) and the feeder fibre across many users. This is especially important in the access network, where the considerable traffic fluctuations across users can be exploited by PONs through statistical multiplexing. The technological and cost advantage of PONs can also be exploited in rural and low-density areas, where larger distances need to be covered in order to provide connections to subscribers that are distributed sporadically over large geographical areas.

FTTH technology has been evolving since the advent of Gigabit PON (GPON) [2, 3]. Most of the progress has focused, in standardisation fora, towards higher rates, with XG-PON, NG-PON2 and XGS-PON. In addition, 25G and 50G PON are currently under standardisation, while 100 Gb/s and above are future targets [4]. Some of the research has nonetheless also considered changes in the optical reach and total split, addressing how this would affect the development of future architectures. The work on long-reach PON (LR-PON) [5], for example, addressed topics such as access/metro convergence, central office consolidation, increase in customer coverage, wide-area protection, etc. Here, the effect of both extending the reach and increasing the split size has showed significant potential for cost savings [6]. Similarly, an extensive study on the requirements of a next-generation optical access networks is provided in [7], which encompasses optical access network technologies, architecture principles, and related economics and business models. Other recent work from Google, on Super-PON [8], also reports considerable savings that result from extending the reach of GPON in a mid-sized U.S. metropolitan area. Firstly, the longer reach brings significant reduction in the number of Central Offices (COs) with active equipment. Secondly, the reduced use of fibre enables the use of smaller 12-48 core fibre cables, which simplifies its deployment compared to the larger 432-fibre cables, thus reducing its cost (for example by allowing the use of micro-trenching). In addition, smaller cables create a positive impact on the cost and time to repair.

The issue of rural area coverage is still widely open. In Europe, FTTH coverage in rural areas is less than half of the total

FTTH coverage, for most countries (according to [9], in the timeframe to mid-2018). We take Ireland as a use case, because about 30%-35% of householders in Ireland reside in rural areas [10], but only about 2% of the total was served by FTTH by mid-2018 [9]. Other use cases in literature include rural Australia [11, 12], where the use of an extended-reach GPON solution was investigated with the aim of lowering both Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) and reducing the number of COs. Other work, targeting fibre route optimisation for long-reach PON rural deployment was addressed in [10, 13].

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, in this paper, we investigate the risk associated to different PON deployment strategies, focusing on rural areas, with respect to different level of end user service take up rate.

In this work, we make use of the LR-PON architecture, as defined in [14, 15], which adopts split ratios of 512 and maximum optical reach above 100 km. Overall, the saving brought by the architecture can be summarised in: (1) reduced number of OLT cards through the increased physical split, (2) reduction in the amount of fibre cables required due to multi-stage splitter design in the Optical Distribution Network (ODN), (3) a considerable reduction in the number of COs/local exchanges and (4) the reduction of electronic interfaces through the convergence of the PON with the metro/regional network [16].

The novelty of this paper with regards to other comparable frameworks can be summarised as follows:

- in addition to considering design concepts necessary to accommodate cost-effective sparse (rural) layouts, we consider the dynamic operation of connecting users to the network and on-demand network expansion. To the best of our knowledge, other studies, although carried out in rural areas, do not consider such aspects;
- we provide insight on how rural FTTH roll-out economics depends on the take-up rate value;
- we agree with the conclusion of our main reference work [7] that the effect of having higher and faster adoption highly impacts the roll-out, but adopt a different approach. While [7] proposes increasing the split/fan-out to reduce the up-front cost, we introduced an additional methodology to trade off the upfront cost. For this purpose, we formulate and designate three diverse duct sharing methods ("long drop" connection methods). In addition, we present the trade-offs of lowering the upfront cost, and discuss the risk associated with using a "long drop" connection method. In particular, we leverage the trade-off between (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 to lower take-up rate than expected).

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

This paper is structured as follows. It begins with a technology review for PON deployment, in Section 2. The "long drop" connection methods are discussed in Section 3. The description of our proposed strategy, is elaborated in Section 4 followed by a description of the pricing scheme and cost model we have considered in Section 5. Section 6 shows our results, while Section 7 illustrates the calculation of the net present value and payback period. Finally, Section 8 concludes the paper.

2. TECHNOLOGY REVIEW

This section elaborates on key aspects and technologies that we consider for rural roll-out. It also provides an introduction to the modelling discussed in Section 4 through a discussion of the effect of network design on our optimisation model and its complexity.

A. FTTH via Long Reach PON

The most common deployment scenario in rural areas involves FTTH, while fibre-to-the-building (FTTB) is typically used to service multi-dwelling units in urban areas. Interestingly, FTTH is recognised as the most viable fibre-based solution for sparser population because of its low operational cost [17, 18]. On the other hand, fibre-to-the-cabinet (FTTC) is used by some operators for initial deployment in an urban scenario before upgrading to FTTH.

The importance of dimensioning and planning has been emphasised in [19]. The work comes up with a dimensioning tool that utilises the clustering algorithm to reduce the required infrastructure. The significance of automated planning and optimisation of FTTx (*x* can be home, building or cabinet) is further highlighted in [20]. There, a method that optimises the network infrastructure with regard to CAPEX by selecting the optimal locations for central offices, fibre collection and distribution points has been discussed.

In general, FTTH roll-out can be implemented in different ways, following a number of architectural choices. A brief survey on several extended-reach PON architectures is available in [8]. In this work, we adopt the LR-PON architecture outlined in Fig. 1. The figure shows the presence of a metro/core (M/C) node which houses all packet processing infrastructure (including OLTs), transponders, and other telecomms equipment (not shown in the figure). Also, the figure shows the PON infrastructure, consisting of optical fibre splitters, amplifiers and ONUs. LR-PONs need optical amplification, with amplified splitters typically located in local exchange (LE) nodes [14]. LR-PON is passive from the point of view of electronic packet processing, which is typically expensive and power hungry. It does however use optical amplifiers at the remote node (which for a LR-PON typically is in a LE location). While requiring power, optical amplifiers typically have low power consumption (i.e., on the order of tens of Watts). The optical amplifiers are placed in the LE to make up for the optical path loss [15, 21]. The amplifiers boost the signal attenuated by large splitting and long-distance

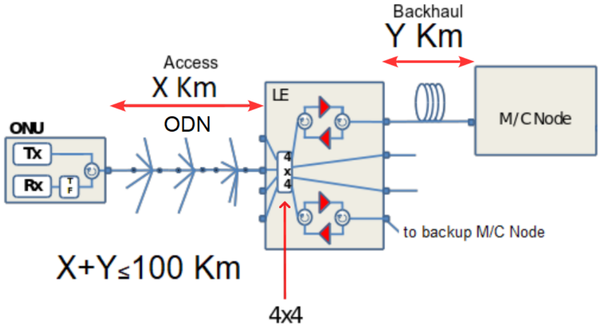


Fig. 1. Long Reach PON architecture outline (backbone network not shown)

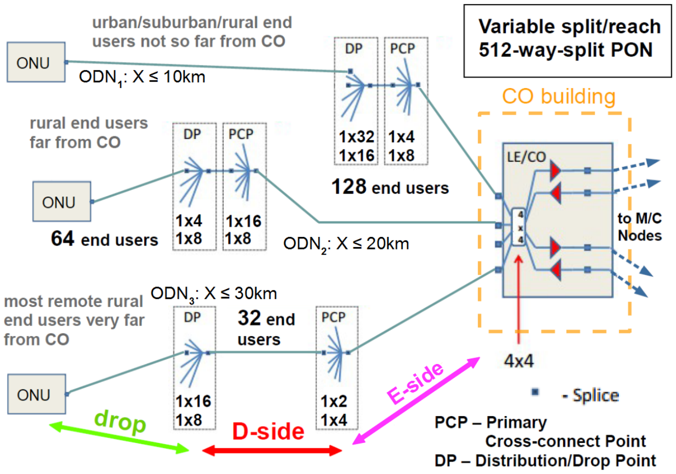


Fig. 2. The access section of LR-PON shows a variable split/reach 512-way-split PON

transmission. Considering the reduced space occupied by amplifiers, the LE buildings could be decommissioned to further reduce costs and the splitter and amplifier located in a cabinet or manhole nearby. M/C nodes are inter-connected through the backbone network that therefore, is outside the scope of this study. In this work, we will focus on the access part of LR-PON and its optimisation. The feeder fibre portion (i.e., between the M/C node and LE) has been already addressed in other studies [6, 16]. Moreover, designing an effective deployment strategy for the access part appears among the most challenging and pressing issues in the rural FTTH roll-out problem. In this paper, we take as reference architecture the LR-PON model with ODN of 10 Km and a 90 Km feeder fibre, which is optimised for positioning the ODN amplification stage in the LE. However, our methodology can be applied to different configurations. In rural areas, where the population is more sparse, localised greater reach can be gained by reducing the number of ONUs in a particular splitter branch. Halving the number of users in a branch gains 3dB power budget equivalent to an increased reach of 10-15km. See section 2.6.1 in [22] for a fuller discussion of reach-split trade-off for rural areas.

Since the proposed LR-PON adopts passive splitters, it is well suited to develop into a multi-wavelength system, in a TWDM-PON architecture, following standards such as NG-PON2. Indeed, studies in [23] demonstrate the possibility to use 40 wavelength channels.

Fig. 2 describes the access section of LR-PON. An amplifier node (e.g., located in a local exchange) accommodates the first stage splitter (4:4), and 128-way-split sub-trees of the PON branch off and reach up to 10 km. In addition, we also allow for the following customisation: by varying reach and split, we can reach remote end-users up to 20 km away (through 64-way-split PON branches), and very remote end-users up to 30 km away (32-way-split PON branches), and so forth, depending on the distance between remote end-users and CO. Controlling the LR-PON's split during its architecture design [6] allows varying the PON's capacity and reach to serve smaller and more remote customer clusters, which is necessary in rural areas.

Also, to describe particular sections of the access network, we employ the following terminology, for the different sections, respectively moving from the end user towards the local exchange: drop section, D-side section (Distribution side), and E-side section (Local Exchange side). We intentionally confine the study to the drop and D-side sections because the highest savings and fibre cable aggregation can be obtained within those sections, i.e., in the closest proximity to end-users. Moreover, our calculations show that the deployment cost of E-side section accounts only for 10% of the total deployment cost as shown in Fig. 10.

B. Passive optical splitters in the ODN section

Once installed, the ODN has low operational expenditure (OPEX) due to its largely passive nature. Indeed, in order to make the ODN deployment viable, passive couplers are typically employed, e.g., optical splitters or arrayed waveguide gratings (AWG) [8]. Our preferred LR-PON architecture only relies on optical splitters in the ODN, in order to avoid wavelength locking.

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 [24]. 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 [19, 25]. 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 [13]. 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.

C. Outside plant: deployment techniques, duct and cabling systems

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 [26], and micro-trenching is under consideration for rural Finnish roll-out [27]. 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 [28] 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 [13].

An important improvement in blown cable systems is the possibility to cover longer distance for a drop cable, up to about 1 km, when Enhanced Performance Fibre Units (EPFU) are utilised [29]. Long-reach drops provide significant opportunities and freedom in developing long drop connections cost-effectively for sparse rural scenarios.

3. "LONG DROP" CONNECTION METHODS

Our goal in 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, we aim 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 [30]. 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), we sacrifice optimal resource management in order to reduce network upfront costs. This approach is required to make the network operation cost-effective from the early stages. We classify the rural roll-out 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. 3. We divide the deployment operations into two main 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. 3). In this paper, we use aerial blown fibre tube (BFT) technology for ducting (more details in Section 5). To investigate the trade-off, we measure the difference between the passing and connecting costs, as a function of end-users take-up rate. In order to make the simulation realistic, we consider that end-users join the network in a random order. In the example in Fig. 3, 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. In ou

- *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. 3). However, it offers the ability to postpone the cost of deploying drops until user-1 or user-2 actually joins the network. In Fig. 3, first, we install a new 2-BFT duct when a user gets connected, and postpone, a new 1-BFT drop deployment to user-2 or user-1, whenever this takes up the service.

- *CM2* - There is no duct sharing as opposed to *CM1* and *CM3* (compared in Fig. 3). Therefore, this option incurs the highest total deployment cost due to costly labour work resulting from the increased number of independent ducts (see Fig. 3). On the other hand, the separation of 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. 3, we can delay the duct provisioning to user-2 until this user joins, as its connection is independent on user-1 ability to take up the service.

4. MODELLING

This section offers insight into the design of our optimisation methodology that is modelled around the physical infrastruc-

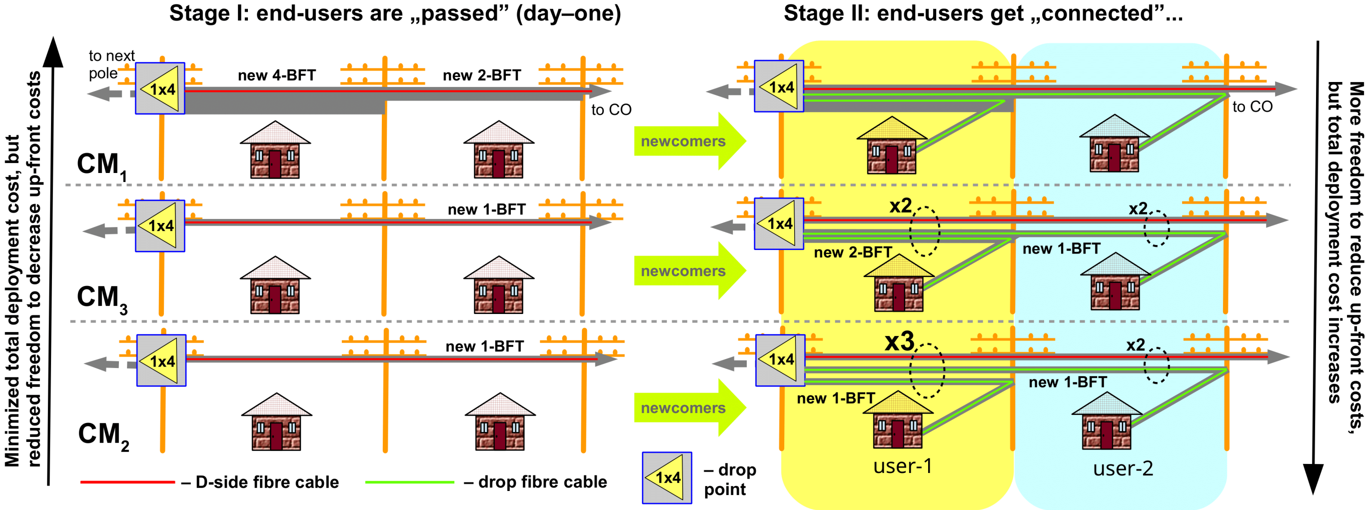


Fig. 3. "Long drop" connection methods: resources sharing is defined primarily through how ducting is shared between D-side and drop sections. This figure represents an effect of clustering described next in Section 4 and Fig. 8.

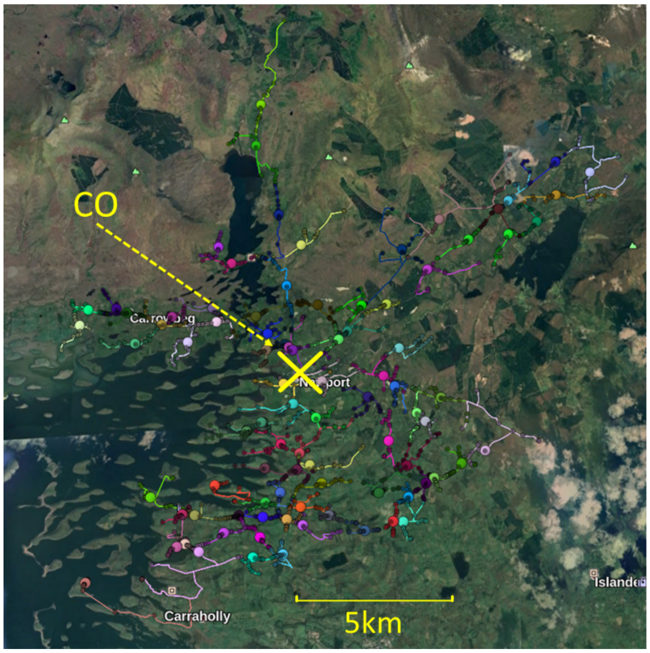


Fig. 4. Our results in the area within the administrative borders of a local exchange in Newport, Mayo county.

ture presented in Fig. 2 and Fig. 3. Our work 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 [31], distributed over an area of about 330 km^2, shown in Fig. 4. 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.

Our scenario considers an area within the administrative borders of a local exchange, currently operating in Newport, Mayo county (Fig. 4). This assumption has a practical justification, since the population in the area is more dense in the town centre with a gradual decline as we move outside the town. In our model, we branch different fibre routes 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 [17, 32].

In the following subsections, we describe our optimisation framework. First, we define a foundation that underpins a heuristic and a clustering algorithm, i.e., a homogeneous multi-stage PON design. We describe how it differs from the standard multi-stage PON design, and how we can benefit from such a distinct approach. Next, we adopt the homogeneous design to formulate a novel clustering algorithm. Upon this single-stage clustering algorithm, we develop a heuristic, a multi-stage clustering algorithm. Also, we explore the factors that motivate the heuristic design. Finally, we provide a background to our techno-economic analysis.

A. 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. We assume homogeneous layout, as this simpler design simplifies roll-out, deployment and the algorithm design. In addition, adopting a homogeneous design allows us to address broader questions, as will be shown in Section 6, such as the overall effect of different split sizes.

Table 1 lists all homogeneous arrangements within a 128 way ODN branch that we examine in this work. Let us first explain the notation used for multi-staging. 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

Table 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+

Fig. 5. 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.

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 be connected to the FTTH service.

The setting in Fig. 1 allows 128-size branches in the ODN below the CO 4x4 splitter; hence, each configuration in Table 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 we support variable length and split size, 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, we can use smaller split size branches that have a lower total split. 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, we gain 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. We implement this methodology in the heuristic in Section C.

B. Fixed-size and street-map-based clustering algorithm

Based on the methodology described in the previous subsection, we propose a novel fixed-size and street-map-based clustering algorithm. The clustering algorithm returns equal-sized clusters (see Fig. 5), 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 NP-hard. A novel initialisation method is proposed in Fig. 6, so that a promising initial solution can be obtained, and thus, a costly polishing phase in Fig. 7 can be mitigated.

```
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
        $P.add(pair(v, dist_v))$
    $SortDescending(P)$
    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
            $P.remove(u)$
    return $Clusts$
```

Fig. 6. The initialisation step: get a promising solution reducing the number of collisions between clusters.

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.

B.1. Initialisation

The algorithm in Fig. 6 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, 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.

B.2. Enhancement

The algorithm in Fig. 7 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, we decided to consider two different types of clustering, described in next Section C. The algorithm operates until no further improvement is found, i.e., there exists no re-connection that improves the solution.

C. The heuristic

The heuristic implements a complex variant of a general problem known as Capacitated Clustering Problem (CCP) [33]. The main goal of the heuristic is to provide a valid multi-stage ODN and optimise CAPEX (defined in Section 5). To fulfil the aim, we combine the single-stage clustering from the previous subsection B to build a multi-stage, i.e. hierarchical, clustering algorithm. Subsequent calls of the single-stage algorithm (in Section B) 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 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 last call. Moreover, since we have assessed that particular algorithms are more suitable for our goals, the heuristic mixes two different types of clustering algorithms:

```
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
                $U_1 \leftarrow U_2$
            $initV \leftarrow minV \leftarrow calcObjVal(c1, c2)$
            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
                        $minV = newV$
                        $bestV1 = u1$
                        $bestV2 = u2$
            if $minV < initV$ then
                $swap(c1, c2, bestV1, bestV2)$
                $improvement \leftarrow true$
                $Update(O, c1, c2)$
    until $improvemnt = true$
```

Fig. 7. Improvement step: reconnect end-users among clusters as long as objective function can be improved.

a) *P-median* [34] - 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. 8 illustrates how the objective function (*obj1*) of *P-median* clustering achieves its optimum;

b) *min-max* [35] - a clustering that minimises the maximum distance to the cluster centre. Fig. 8 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 we aim to minimise. More specifically, the former clustering approach attempts to minimise the ODN cost, while the latter method leads indirectly to minimise the number of PONs and thus the number of OLT cards. P-median and min-max clustering algorithms have different objective functions, and therefore, we employ those methods 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 and $calcObjVal(c1, c2)$ in Fig. 7 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. 8. 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 and $calcObjVal(c1, c2)$ in Fig. 7 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 [14]), 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.

5. 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 our 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 [36]. A sensitivity analysis is given in Section 6.C, so that the results can be analysed against variation in some of the key costs.

A. Ducting

The construction cost of ducting infrastructure varies significantly and depends on many factors. Trenching is one of the most expensive techniques. According to [37], civil work for digging trenches accounts for up to 80%-90% of total FTTH investment in a rural Danish scenario. This strongly motivates us to consider more cost-effective alternatives, such as aerial ducting. Similar to the Danish scenario, but also occurring in other countries [38], we also assume 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, our model 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 [39], [40], [41], [42].

The solution considered here for ducting is blown fibre tube (BFT), employed in a real-world FTTH roll-out by European operators [43]. A BFT is a plastic tube consisting of a number of smaller sub-tubes. Since, we target cost-effective deployment, we need to consider a wide range of BFT sizes to address 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 2 in row C1 and were derived from operators data.

We investigate the cost of duct installation (i.e., labour) in Table 2 in row C4 separately, as it can vary considerably. Practical deployment sources [26] show the possibility to carry out duct installations at the rate of 4 hours per kilometre, for a two-worker

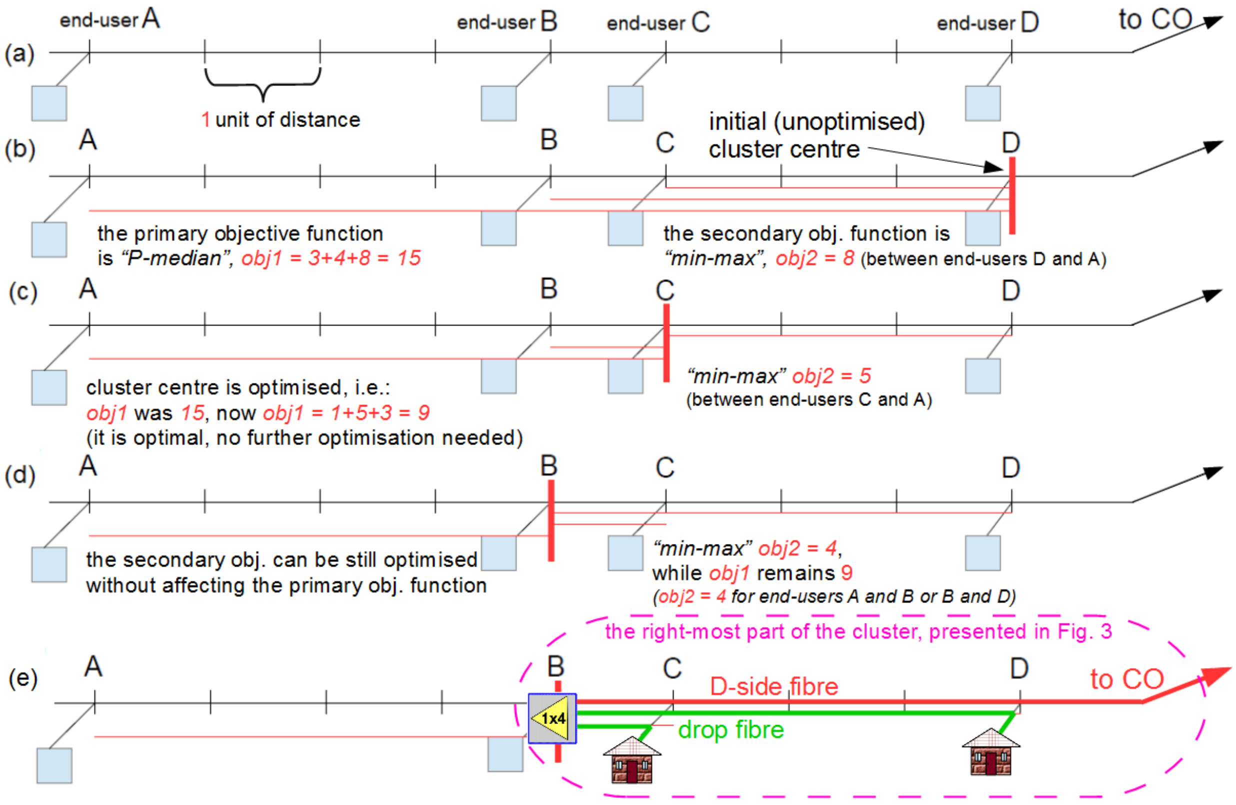


Fig. 8. House-connecting stage clustering with *P-median* as the primary objective function and *min-max* as the secondary objective function. P-median optimises the amount of fibre used, i.e. its total length which is calculated in Figure (b) as a sum of distances between end-users and the cluster centre. 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.

Table 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 4) which dimensions the size of duct links planned along the streets according to required fibre capacity and particular deployment scenario (Fig. 3). So, it is known in advance what variant of BFT to install in both stages in Fig. 3.
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 4) to interconnect the ducts. C_t^2 set contains both material and labour costs, and BoM (Bill of Materials) is illustrated in Fig. 9. 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 4) 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. 3.

team. We also take 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 [26] 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 [44]. Since the fibre network deployment techniques constantly improve, we may expect further improvement in installation time.

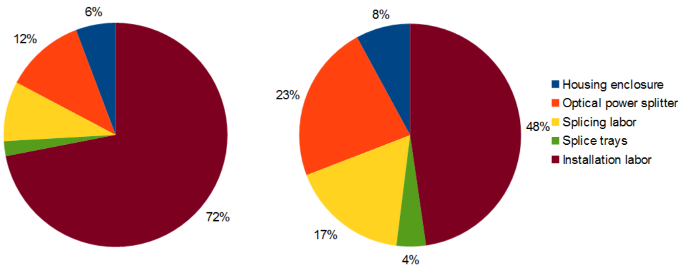


Fig. 9. Sample 2-size (on the left) and 8-size (on the right) splitter/splice nodes, and their composite cost share.

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. 3. Onsite visit also involves the construction work to deliver the link between the end-user's home and the closest street. The cost of this link is taken into account in NPV analysis in S_{avg} cost in Section 7 because the cost is not relevant when comparing the connection methods in Fig. 11.

B. Splitter/splice nodes

A splitter/splice node is an enclosure designated for optical power splitters installation and fibre splicing. We consider multiple node variants to serve cost-effective deployment both in sparser and denser rural areas. Splitter sizes and pricing are summarised in Table 2. The total cost of a single node in Table 2 includes: housing enclosure, optical power splitter, splice trays, splicing and installation labour. Fig. 9 shows two variants, i.e. 2-size and 8-size, splitter/splice nodes and their components cost share.

C. Blown fibre (cabling)

Once a duct network and splitter/splice nodes are in place, blowing the fibres into the ducts can be initiated. We consider a blown fibre unit (BFU) for the purpose [43], 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 2.

6. RESULTS AND TECHNO-ECONOMIC ANALYSIS

In this section we implement the three different deployment solutions described in Section 3. Our goal is to compare their applicability to different scenarios and to identify what types of costs affect the deployment more in sparsely populated areas. As variable parameters we consider: take-up rate, deployment model and splitter configuration. We adopt the CM1 strategy, intended for low-risk scenarios, as the baseline for our comparisons.

In Section D, we attempt to devise a methodology designated for variable take-up rate analysis. In other words, we make a simulation, 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. Our aim here is to estimate, for all methods in Section 3, the extent of that cost fluctuation. As we have already mentioned in the abstract, operators may be more interested in rural roll-out if they know the risk associated with particular take-up rate values. Moreover, we are specifically interested in estimating a hypothetical average deployment cost for each method. Having such an average estimation, we can make a sensible comparison in Section E. In addition, we are also interested in showing cost figures for various duct installation speeds. This enables a discussion on whether a research on faster deployment techniques is worth considering.

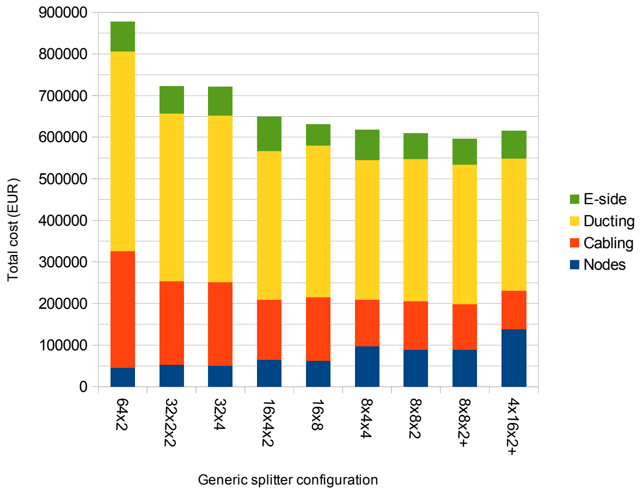


Fig. 10. Total deployment cost for different splitter configurations available within default connection method CM1, all end-users are connected (100% take-up rate).

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

We begin by examining the total deployment cost for a low-risk service take-up scenario, where we assume the maximum user uptake, in order to provide a lower bound reference point for the comparison. Fig. 10 reports the deployment cost, calculated for our rural Ireland use case shown in Fig. 5. In the x axis, the splitter configurations are arranged in descending order with respect to the last stage splitter size.

We can see a trend emerging: 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, we can see 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+*.

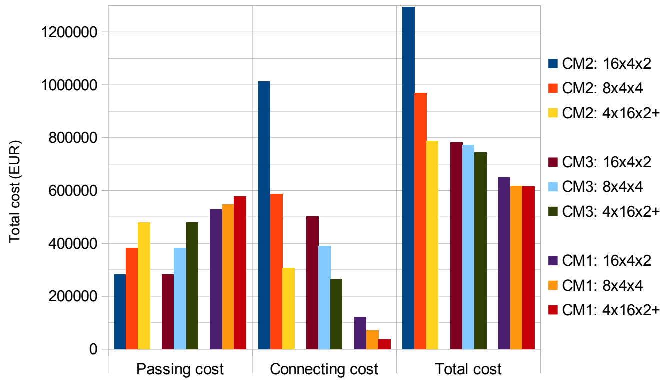


Fig. 11. Passing and drop costs for different connection methods, all end-users are connected (take-up rate is 100%). Total cost is equal to t_c in Equation 1.

B. Passing, drop, and total costs trade-off

In order to account for variable take-up rates, we first 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.

Examining such trade-off for the different connection methods, Fig. 11 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. 11 is calculated as follows:

$$t_c = \sum_{t\in T_1} C_t^1 \cdot duct_t^{len} + \sum_{t\in T_2} C_t^2 \cdot node_t^{count} + \sum_{t\in T_3} C_t^3 \cdot fibre_t^{len} + \sum_{t\in T_1} C_r^4 \cdot duct_t^{len} \qquad \mathbf{(1)}$$

, where:

- t_c - the total deployment cost shown in Fig. 11
- $duct_t^{len}$ - the length of duct of particular type $t \in T_1$ required in a deployment. This value is yielded by the heuristic in Section 4.
- $node_t^{count}$ - 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 4.
- $fibre_t^{len}$ - the length of fibre cable of particular type $t \in T_3$. This value is yielded by the heuristic in Section 4.
- r - duct installation rate, $r \in T_4$, which is constant in a single experiment (deployment)

	All component costs of the total deployment cost (t_c) in Equation 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 3. Sensitivity analysis of the total deployment cost (t_c) caused by 10% increase (or decrease) in all component costs illustrated as percentage share.

C. Sensitivity analysis

A sensitivity study of the parameters in Table 2 was performed and shown in Table 3 and Fig. 12. The figure and table measure the sensitivity of the total cost (Fig. 11) 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 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. 3). In effect, CM1 involves less ducting, and therefore, it is less subjected to an increase (or decrease) in the duct installation cost.

D. Measuring the effect of fluctuations in users take-up

In this section, we analyse 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, we plot best and worst-case cost curves, which provide a lower and upper cost boundaries for all other possible outcomes. We distinguish the following curves:

- Best-case cost curve: end-users that incur the lowest drop cost join first. We formulate and employ a greedy algorithm to generate this type of curve;
- Worst-case cost curve – a reverse to best-case curve, i.e., end-users that generate the highest drop cost join first. Again, we formulate and employ a greedy approach to compute this curve;

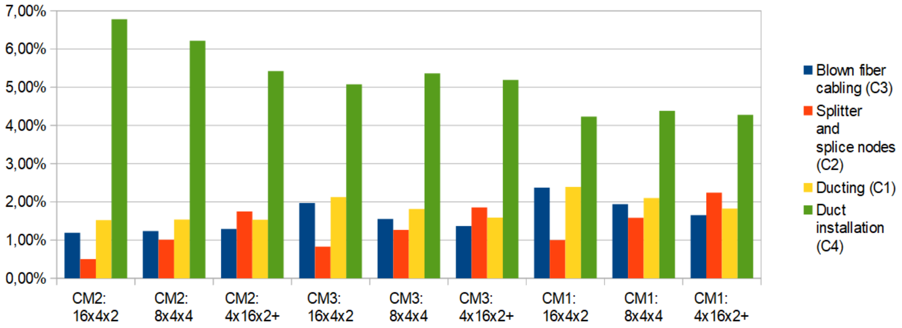


Fig. 12. Sensitivity analysis of component costs as a result of 10% increase (or decrease) in total deployment cost (t_c).

- 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. 13, the mean is calculated over 10^5 random curves;
- The upper and lower percentile curves, in Fig. 13, 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.

We illustrate sample curves for all connection methods of *CM: 8x4x4* in Fig. 13. 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. 13 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, we embrace an approximated curve 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. 13. 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. 14, we extend this analysis to all deployment methods and splitter configurations. Namely, the evaluation in Fig. 13 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, we define a hypothetical threshold that at least 30% uptake must be reached for viable network operation (marked with a blue dashed line), similarly to [45].

In Fig. 14, 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. 13 and Fig. 15. 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. 15.

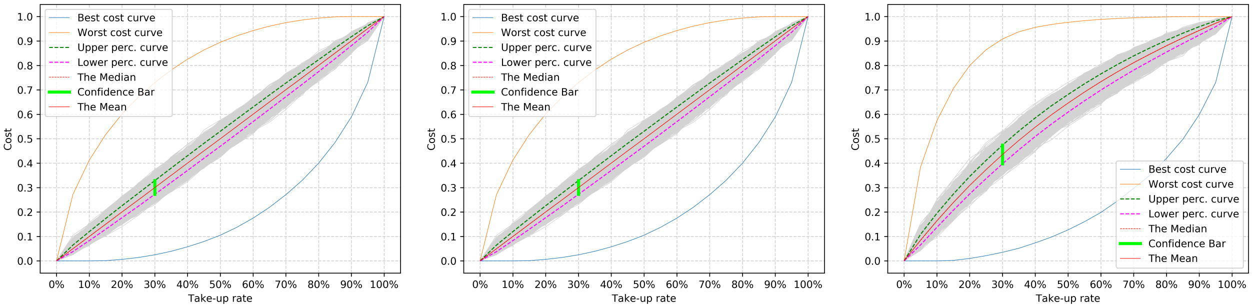
As mentioned above, for higher-risk rural scenarios, it is important to keep the initial cost low. For this reason, in this work, we also examine cost figures that are around 30% take-up rate and below, as the rural scenario is high-risk, and it is important to analyse its viability at lower take-up values. Even if commercial operators might not have a viable business case, it is important for other players (e.g., municipalities or central governments) to understand the trade-off between different strategies. In Fig. 15, option CM3: 16x4x2 guarantees the lowest deployment cost at 30% take-up rate (best-case cost curve). Fig. 14 and Fig. 15 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. 15, we report a similar analysis 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. 15. 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, we can see that in principle different strategy can have considerable difference in cost, depending on how the users join the network. If we focus 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. 15). The next section brings an additional, highly relevant, perspective into the discussion: the cost per customer connected.

E. Cost per customer connected

The next parameter that we 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. 16 compare CPCC for all methods, also considering different duct installation rates (DIR). Generally, a lower *CPCC* should encourage a higher number of customers to subscribe to the fibre-based services. Our cost figures are relatively lower compared to the cost of 1500 EUR/customer installation fee proposed for rural Swedish scenario [17], although here a direct comparison is not possible since our study assumes existing electric post infrastructure and excludes ONUs cost.



(a) CM1 **(b)** CM2 **(c)** CM3

Fig. 13. 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.

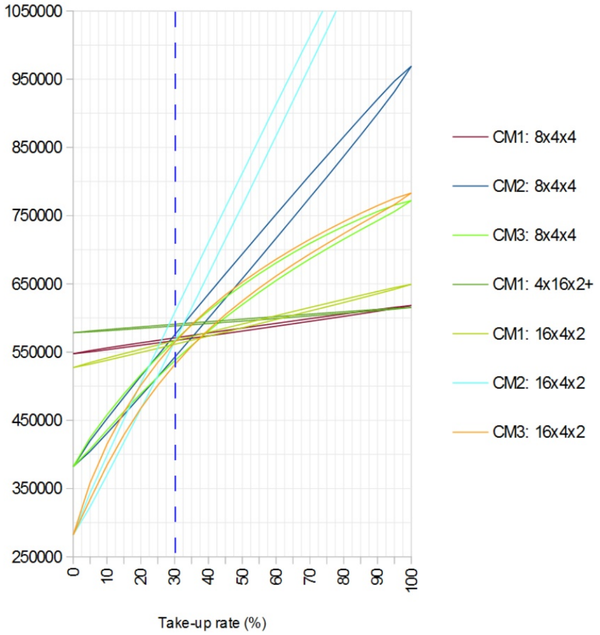


Fig. 14. Cost uncertainty area enclosed between upper and lower percentile curves for all connection methods.

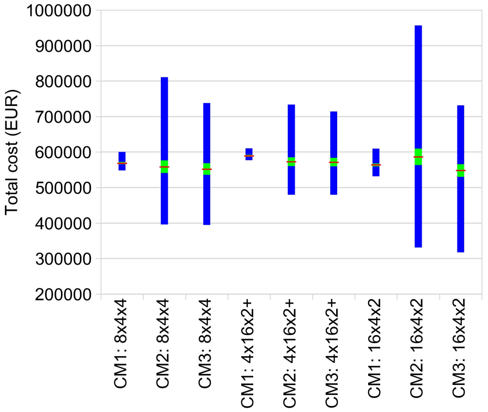


Fig. 15. Cost error bars at 30% uptake: a) average cost – the mean (red marker), b) confidence bar (green segment), c) potential deviation towards worst-case and best-case curves (blue segment).

Interestingly, Fig. 16 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 pivoting 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. 3. 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. 3.

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.

F. Discussion

This section provides an overall summary of the findings described in the previous sections. Firstly, our 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, we showed for a specific use case, based on realistic data (i.e.,

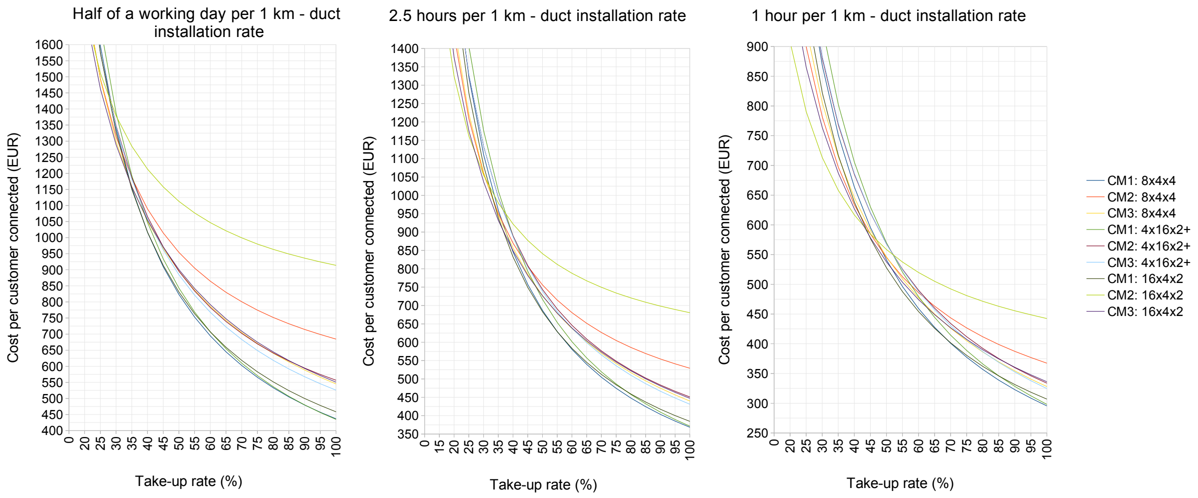


Fig. 16. Cost per customer connected curves for different duct installation rates.

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.

We then showed that among those, CM3 presents a lower cost variance with take-up. Finally, we 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 our analysis, by reporting the net present value calculation for the preferred option.

7. NET PRESENT VALUE AND PAYBACK PERIOD

In this section, we calculate net present value (NPV), 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 that we assume is 40 years). This is in line with other studies such as [46] in Sweden;
- r is the discount rate: we assume 3% in our examination;
- 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. We assume that S_{avg} equals 2,000 EUR in Table 4. For instance, [46] 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 5, we report additional results for S_{avg} values of 1,000 and 4,000 EUR;
- 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, we do not explicitly consider OPEX and revenue values, but we use the simpler profit as variable. The value of profit can be higher than in Table 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. 5, we report the minimum profit value that operators should assure in order to reach a viable payback time;
- F is the value of one-time installation fee per end-user;
- C_t is the total yearly profit from all end-users, we assume it is constant and equals $P * N * 12$.

Table 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 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 4. Payback time for *CM3: 16x4x2* (the random end-users connection order, duct installation rate: 1km/1h)

8. CONCLUSION

In this paper, we have examined different FTTH deployment strategies for rural areas. Our work highlighted how deployments in rural scenarios affect not only the overall economic viability, as 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).

After having investigated the relationship between cost and service take-up rate, we identified a significant difference in network cost (per end user), depending on the expected take up rate. Furthermore, we have assessed the impact of duct-installation speed on the deployment strategies in terms of economic efficiency.

We have evaluated our study 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.

			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 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.

Our results have shown that the specific deployment strategy selected can make a considerable difference on the overall deployment cost and thus in the economic viability. For example, 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 us 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%.

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