Redesigning the UK Broadband Network by Monte Carlo Simulation

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The UK telecommunications network consists of over 5,500 exchanges that are used to deliver broadband and communication services to the majority of households. This infrastructure is rapidly becoming inadequate for supplying the data transfer needs of customers. This is partly due to population growth and migration, but mainly due to demand for bandwidth hungry internet services, for example high definition television and video conferencing. One solution that is currently being considered is to upgrade the network to use fibre-optic cables. Fibre optic cables have higher data transmission rates than the copper cables currently used and have lower attenuation.

One way to minimise the costs of deploying a fibre optic network is to reduce the number of exchanges used, saving the money needed to maintain those exchanges. We attempt to determine the most profitable way to upgrade the network: optimising replacement of fibre optic cables and de-commissioning of exchanges. Since this is a combinatorial problem we use simulated annealing to find the optimal upgraded network.

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1 Introduction

The UK was the first country to have a commercial fibre project launched way back in 1975 when everyone predicted a great future for optical fibre data communication.1) Several decades of experiments, trials and localised deployments followed, none of which helped optical fibre technology through the cost barrier and into the mainstream of network deployments. That is, until recently. With 24 of 30 OECD countries now rolling out fast optical fibre services nationwide, the need for more speed, bandwidth and network capacity that allows faster residential broadband services has been acknowledged in most OECD countries. But in the UK, the debate is still ongoing and only slowly moving forward.

Of all the major European nations, the UK has shown the least inclination to move toward optical fibre. Several localised initiatives are pursued by private investors and real estate companies that are building new homes.2) There is also one major municipal project called Digital Region South Yorkshire that involves bringing high-speed broadband to 500,000 houses, though it is not clear at this stage how many (if any) will be connected using the all optical fibre version of Fibre-to-the-Home (FTTH).3)

To achieve a national coverage of fibre services, the incumbent BT has to be on board. Until June 2007, BT management stuck to its first line of defence. So we could hear that *"... as long as the [copper-based broadband] service works [customers] don't give two hoots about speed."*4) A little later in July 2007, a U-turn followed and BT's chairman admitted that BT was again contemplating a watered-down version of optical fibre to the street kerb (FTTC) which could deliver up to 50 Mbps.5) No business case for the nationwide deployment of optical fibre was, however, presented until July 2008.

BT now plans to invest GBP 1.5 billion in a fibre network upgrading programme that will aim to connect up to 10 million UK households by 2012. BT will initially invest GBP 100 million per annum in

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1) *Hecht, J. 2004. 'City of light. The story of fiber optics'. Oxford: p.177.*

2) *Walsall Project: as of 24/01/2007, Walsall Urban Regeneration Company (WRC) is looking to establish a GBP 500m physical regeneration project that will include FTTH services for 1,100 and a further 200 new homes per year up to 2010.*

3) *Digital Region South Yorkshire (2006), http://www.digitalregion.co.uk/index.html, accessed on 8 August 2008.*

4) *Angus Flett, BT Wholesale's director of product management, as quoted in The Register of 4 June 2007, Chris Williams (2007) 'BT declares ceasefire in broadband speed wars', http://www.theregister.co.uk/2007/06/04/bt_speed_wars_over/, accessed on 8th August 2008.*

5) *Sir Christopher Bland, BT Chairman, as quoted in the Financial Times and in The Register of 19th July 2007, Kelly Fiveash (2007) 'BT feels the need for 50 Mb speed', http://www.theregister.co.uk/2007/07/19/bt_faster_broadband/, accessed on 8 August 2007. BT Openreach has also announced in Feb 2007 that it will trial FTTP in a greenfield deployment at 9,500 new homes in Ebbsfleet, South England until late 2008, before deciding whether to carry FTTP into brownfield deployment, http://www.ebbsfleetvalley.co.uk/, accessed on 8 August 2008.*

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2008/09 and 2009/10 for trials in London and Cardiff. A further GBP 800 million will be spread over the following three years.6) The pilots will start in summer 2009, together with BT Openreach, and are expected to go commercial in 2010. Once the trials are completed, users will have access to service download speeds of up to 40 Mbps.7)

Cost is the ultimate barrier to the deployment of optical fibre. This is often stated, repeated and reiterated. In particular national deployments are stalled by the potential costs. The largest cost item in developed countries is labour cost, that is, the cost of digging up streets to lay new cable conduits. The more digging is required, the higher the deployment cost. Some operators have opted for partial solutions that reuse existing conduits, air-blown fibre installation, or large sewage systems.8) In all these scenarios, physical space and distance play an important role in defining deployment costs.

Predicting what fibre-optic deployments will be made in the UK is a complex task. In this article we approach this question from a financial perspective. It is very likely that the fibre-optic network for which the strongest business case can be made will be the one actually constructed. Thus we focus on the problem of finding a network upgrade which maximises the return on investment, enabling us to forecast the spread of fibre-optic networks in the UK. We here develop a mathematical model that estimates the expected return on investment for a given network upgrade. Using this we can then forecast an optimal upgrade proposition by solving the combinatorial optimisation problem of maximising return on investment using Monte Carlo simulation.

Our approach differs from other modelling studies in this area in two respects. Firstly, we use detailed small-area estimates of broadband subscriber numbers at UK postcode resolution. Secondly, previous studies have made a priori choices about the location of the upgrade, deciding in advance which subscribers and exchanges to upgrade. In our approach, the algorithm chooses the scope and thus the location of the upgrade in order to maximise return on investment.

2 Methodology

With European incumbent operators partly or fully privatised, companies find themselves charged with deciding how to fund network infrastructure and technology upgrades within existing and potential revenue expectations. Overall strategy, choice of vendors, legacy architectures and local geography will all impact on what decision is being made and whether a business case could be fitted to that deployment of fibre technology.

There are two visions of future bandwidth needs and of demand on operator networks. These two visions are not mutually exclusive, but complementary. New multimedia services have caused network operators worldwide to anticipate a rise in bandwidth demand per household in the range of 20 to 50 Mbps over the next five to ten years. In more aggressive assumptions, this estimate can be anything between 50 Mbps and 100 Mbps.9) Depending on a company's vision this leaves room for two main scenarios:

- A partial replacement of copper in the access network with optical fibre, run from the central office or telephone exchange to the local street cabinet: Fibre-to-the kerb/cabinet (FTTC), with service speeds of up to 50 Mbps; or

- A total replacement of copper in the access network with optical fibre, which is run all the way from the telephone exchange to the home: fibre-to-the-home (FTTH), with service speeds of up to 100 Mbps.

As the recent moves of South Korean operators show FTTC is a natural step in the evolution to full optical fibre networks.10) FTTC were initially deployed by incumbents to reduce investment risks. Seeing the leading broadband nations Japan and South Korea, who pioneered optical fibre services, begin upgrading from a mixed optical fibre + copper LAN networks

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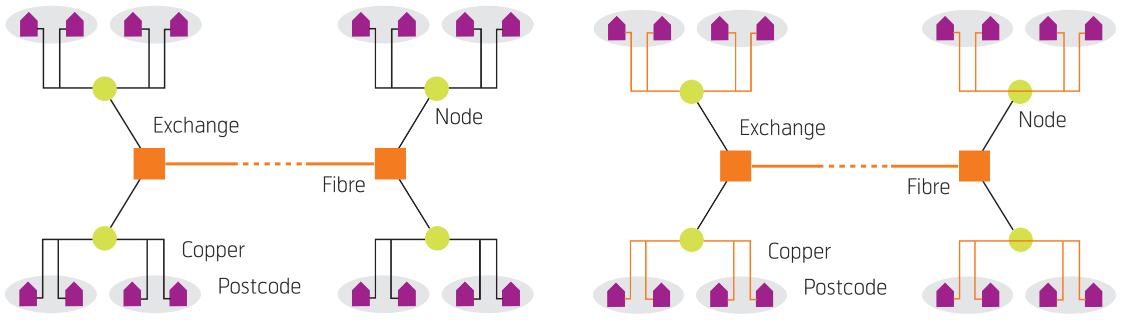
6) *BT Group (2008) 'BT plans UK's largest ever investment in Super-Fast Broadband', http://www.btplc.com/News/Articles/ShowArticle.cfm?ArticleID=efd7b1fa-52ed-45bb-b530-734fac577e94, accessed on 23 August 2008.*

7) *BT Group (2008),Openreach announces fibre pilot sites', http://www.btplc.com/News/Articles/Showarticle.cfm?ArticleID=a900092c-60cd-4ea9-a880-4156c01bbbea, accessed on 16 October 2008.*

8) *Jeyaplan, J.K. (2007) 'The Pipe Is There: Using existing infrastructure to Speed FTTH deployment', Broadband Properties: March 2007: 61-70, http://www.broadbandproperties.com/2007issues/march07issues/jey_mar.pdf, accessed on 8 August 2008.*

9) *Goderis, D. (2006). 'The need for speed. Next-generation access with VDSL2' In Alcatel (eds.) Breaking the barriers. A guide to transforming your access network. Paris: 63-71.*

10) *In Feb 2007, KT announced that it will invest a total of KRW 402.4 billion in deploying the FTTH service and improving the quality of existing subscriber networks by supplying a total of 380,000 fibre cables to residential areas in the first quarter of 2007 and additional 310,000 cables in the second quarter, while also building 674,000 lines with up to 100 Mbps download speed in order to expand the LAN and VDSL services for apartment complexes. Korea Telecom News Release (2007). 'KT launched 100% FTTH service for home', http://www.kt.co.kr/eng/New/pr_news_kt_view.jsp, accessed on 8 August 2008.*



a) Current network

b) FTTH

Figure 1 a) Current network topology. Subscribers are connected to exchanges via copper cable which are amalgamated at nodes. Exchanges are connected to each other by fibre-optic cables. b) 'Fibre-to-the-Home' network upgrade. All copper cables are replaced by fibre-optic cables

to pure optical fibre FTTH networks, suggests that FTTH is the future. So here we model an all-optical fibre network that replaces all existing copper network parts between the exchange and the home with optical fibre wiring (Figure 1).

In order to find the optimal upgrade for a given network we need three main sets of information. First, there is location of the exchanges and subscribers, and how both are currently linked to each other. Second, what is the spatial distribution of the population/households within the network – which may be different from the distribution of a network operator's subscriber base? And lastly, we need to establish a set of parameters that allow us to estimate the total profit and return on investment (ROI) that can be obtained from an upgraded network, calculated over a specific period of investment. Network information as well as population data at postcode level was kindly provided by Point Topic Ltd., a London-based broadband analysis company, for the purpose of this research.

In the UK, a postcode refers to a geographic area about the size of a small section of a street or several neighbouring houses. Most postcodes contain between 10 and 30 households. Small and medium-sized businesses can sometimes be allocated their own individual postcode. Such postcodes contain no resident households and are excluded from this count (Figure 2). Based on the socio-economic make-up of each postcode (= the resident households within it) and industry data, Point Topic has then estimated the number of broadband subscribers which we use as input to the model.

Since exact digital topological network information is proprietary and not publicly available,11) we have assigned each postcode to the closest telephone exchange by default. Should actual topological network data become available, this can easily be integrated into the model.

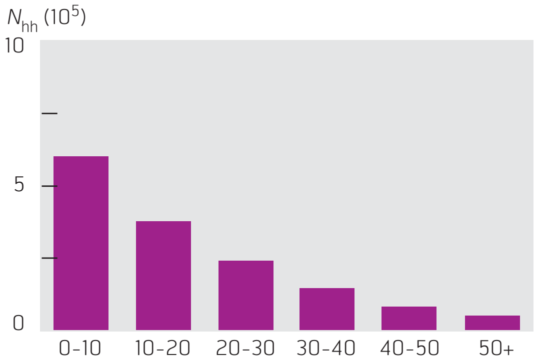


Figure 2 Histogram of postcodes binned by the number of households they contain

2.1 Cost Model

The profit that can be made from a given network may be calculated from revenue from subscribers and expenditure. When considering an upgrade we can separate expenditure into operating costs for the network and the cost of upgrading the infrastructure. In industry-terms, revenue per subscriber equals ARPU (average revenue per user). Substantial one-off, upfront costs can occur to convince the user to join a service and to get the user connected the network. In the majority of cases, network operators cover these costs. In far fewer cases, new subscribers pay a one-off fee, contributing to covering the cost. Over the life-time of a subscription, subscriber acquisition cost (SAC) and installation cost reduce ARPU. In the modelling here, we have not included SAC. We per-

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11) *In April 2008, BT Openreach, the network division of the BT Group, launched New Network Engineering Journey Project (NEJ). At its heart is a process that will eventually result in a digital network inventory that may prove useful to spatial simulation models introduced here. Disparate paper network plans from filing cabinets across the UK are digitised into a web-accessible geographical information system that wil be invaluable for network planning and maintenance. A pilot covering two of the largest London exchanges was completed by that time. Source: BT Openreach Analyst Briefing of 16 April 2008, Wood Green, London.*

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ceive this to be part of the marketing expenditure. But we have included a variable: 'cost of household upgrade' that allows us to model the cost of installing a service for the subset of households that want to subscribe.

The business segment also offers important revenue opportunities for the network operator, even if the residential market is the largest. Network operators commonly want to have or retain a foothold in both segments. The residential market offers scale and low ARPU, the business segment promises low scale and high ARPU. This paper and the parameters it uses are focused on the residential market. ARPU figures and geo-demographics would have to be adjusted to cater for a more detailed optimisation of residential as well as business users. So in our scenario, that of fixed-line services, there is only one user/subscriber per household. The revenue per household may increase with the number of people or individual users being part of the same household. This correlation has not been explored here. So each UK household represents one revenue opportunity only. Mathematically we express this as

$$P = R - E \tag{1}$$

where P is profit, R is revenue and E is expenditure. This profit is calculated for the period of time investors are willing to wait for a return on investment.

2.1.1 Revenue

Income from the network comes from fees paid by subscribers. In this model we consider two types of subscribers: those with a DSL connection who pay an average subscription fee of r_{dsl} and those with a fibre connection who pay an average subscription fee of r_{fb}. The total revenue is thus

$$R = \sum_i n^{pc}_{bb,i} r_{fb} + \sum_j n^{pc}_{bb,j} r_{dsl} \tag{2}$$

where index i runs over postcodes with fibre access, index j runs over postcodes with DSL access and $n^{pc}_{bb,i}$ is the number of households in postcode i with broadband subscriptions.

There are two possible interpretations of the quantity r_{fb}. The first interpretation is straightforward: r_{fb} is the actual revenue obtained from a broadband subscriber with fibre access. A second, more subtle interpretation is also possible: the parameter r_{fb} can also be considered as a Lagrange multiplier. If, for instance, a company was willing to upgrade its infrastructure without increasing subscriber costs, setting r_{fb} to an artificial value within simulations can be used to target investment to benefit the largest number of subscribers and to control the amount of investment needed.

2.1.2 Expenditure: Capital Expenditure and Operating Cost

As described above expenditure E can be subdivided into operating costs O and upgrading costs U.

$$E = O + U \tag{3}$$

The operating costs of the network are primarily those associated with maintaining the exchanges. In our model the nature of the exchange determines the operating costs. DSL exchanges are the most expensive to operate. The upgrade of an exchange to fibre replaces the equipment in the exchange with components which require less maintenance and energy. Optical fibre wiring also allows for large distances between users and exchanges, making exchanges redundant when networks are redesigned. A decommissioned exchange requires no maintenance and permits considerable savings on overall network running costs. The operating costs O are given by

$$O = O^{ex}_{dsl} N^{ex}_{dsl} + O^{ex}_{fbl} N^{ex}_{fb} \tag{4}$$

where O^{ex}_{dsl} is the operating cost of a DSL exchange, O^{ex}_{fb} is the operating cost of an upgraded exchange, N^{ex}_{dsl} is the number of DSL exchanges, and N^{ex}_{fb} is the number of upgraded exchanges.

We can categorise the upgrade cost U into several categories: 1) cost of upgrading exchanges to fibre or installing a brand new one, 2) cost of digging ducts between postcodes and their exchange, 3) cost of blowing the cable itself, and 4) cost of completing the connection from the postcode to the individual subscribers. So the upgrade cost U is

$$\begin{aligned} U &= \left(C^{ex}_{ug} + C^{ex}_{inst}\right) N^{ex}_{ug} + \\ &+ \sum_i \left(C_{dig} d_{pc,i} + C_{cable} d_{pc,i} n^{pc}_{hh,i} + C^{hh}_{ug} n^{pc}_{bb,i}\right) \end{aligned} \tag{5}$$

where C^{ex}_{ug} is the cost of upgrading an exchange to fibre, C^{ex}_{inst} is the cost of building a new fibre exchange, N^{ex}_{ug} is the number of upgraded or newly installed exchanges, summation is over upgraded postcodes, C_{dig} is the cost per unit length of digging trenches, C_{cable} is the cost of buying and blowing cable, C^{hh}_{ug} is the cost of connecting a single household, $n^{pc}_{hh,i}$ is the number of households in postcode i, and $n^{pc}_{bb,i}$ is the number of broadband subscribers in postcode i. Note that in the final term the connection between the postcode centre and individual houses located in that postcode is only made for subscribers and not all households.12)

2.1.3 Distance

When copper-based telephone networks were initially deployed, they were largely done to a standard design with public funding and over many decades. The result is a patchwork of lines, street cabinets, nodes and telephone exchanges that connect each household to the network, but not necessarily in the most efficient way as today's business environment requires. Old networks were solely designed to carry PSTN voice and low volume data traffic. In the context of network upgrades, efficiency may be defined in a number of ways: first, in terms of the optimal physical routing of fibre connections within an area, second, the number of households that are connected to an exchange or central office and lastly, the bandwidth capacity that is allocated to each end user.

Networks can have different structures. Typically an access network has a tree structure from the fibre node to the home or multi-dwelling unit. Some access networks have integrated fibre rings that ensure network redundancy which increases investment volume. In all these contexts, physical distance and its definition are crucial. We find that the meaning of distance $d_{pc,i}$ as used in the equation above needs some discussion.

Consider digging a network to connect upgraded postcodes to an exchange. Figure 3a shows a randomly generated collection of postcodes and an inefficient connection strategy: each postcode is connected to the exchange by a direct tunnel. This strategy is very wasteful. Figure 3b shows a much more spatially efficient strategy that connects several postcodes via the same route to the exchange. This efficient network is generated by the following algorithm.

For each postcode:

- from the set of other postcodes closer to the exchange find the closest postcode,

- if this postcode is closer than the exchange connect these two postcodes,

- if the exchange is closer, or there are no postcodes closer to the exchange connect the postcode to the exchange.

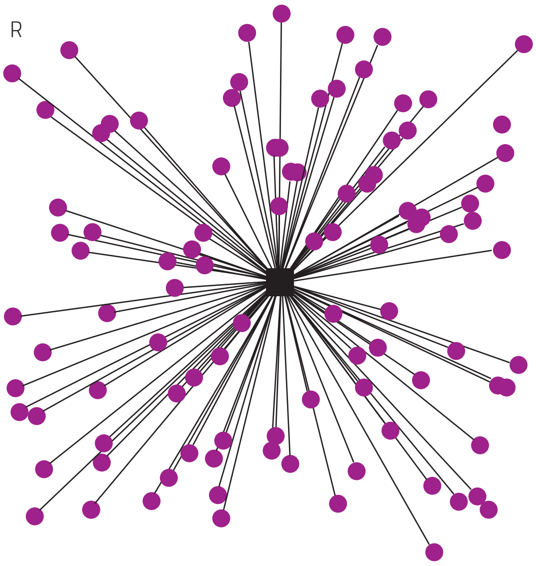

Figure 3a An inefficient network. Each postcode is directly connected to the exchange. The total length of fibre optic cable required is R

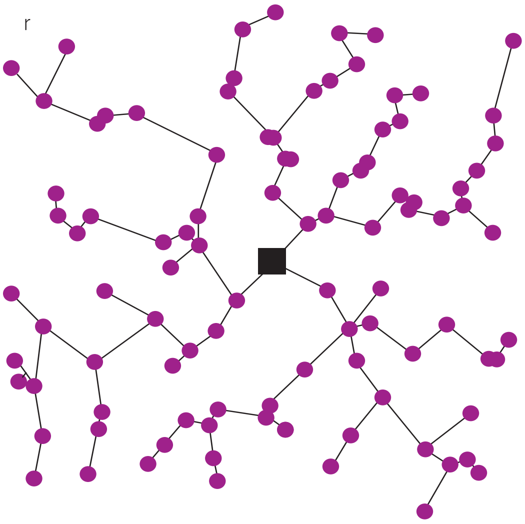

Figure 3b A more efficient network. The total segment length is r

When calculating the length of fibre optic cable needed to connect a postcode to its exchange we need to use the full distance from the exchange to the postcode. However, when calculating the length of ducts that need to be excavated for a postcode to be connected to an exchange, we need to account for multiple usage and sharing of a duct between several postcodes. In principle, the algorithm just described above could be incorporated into the calculation. But this would slow down the calculations considerably. Instead the calibration curve shown in Figure 4 is used. This was plotted by calculating a network for each of the exchanges in the current UK network, and fitting the results to a curve:

$$\frac{r}{R} = \frac{a}{\sqrt{n}} \tag{6}$$

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[12] *Here we account for a typical network building approach that involves 'Homes Passed' – those that can be connected on request with additional cost from nodes, distributers or basement cabinets that have been installed earlier, and 'Homes Connected' – those that are connected to the physical network already.*

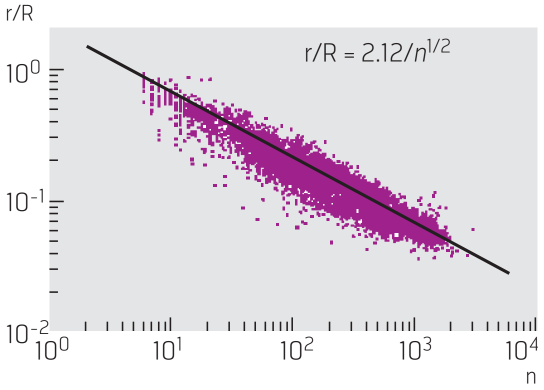

Figure 4 Distance calibration curve. Data points are network segments for each exchange calculated from the existing configuration of exchanges. The line is a best fit calibration curve

where r is the tunnel length for a network of the type described above, R is the length of a network in which each postcode is connected directly to the exchange, a is a fitting parameter and n is the number of postcodes connected to the exchange. This form of the equation assumes that the fraction r/R is inversely proportional to the square root of the number of postcodes sharing the exchange.

2.2 Algorithm

Finding the network which maximises profits is an example of a combinatorial optimization problem. Each of the components of the problem can be in one of a number of states: the subscribers in a postcode can be connected to their exchange by fibre or by copper; exchanges can use the DSL protocol, be upgraded to fibre or be decommissioned. The key feature of these types of problems is that the number of possible combinations rises exponentially with the number of elements in the system. Even for an apparently small number of elements it is unfeasible to systematically explore every possible combination.

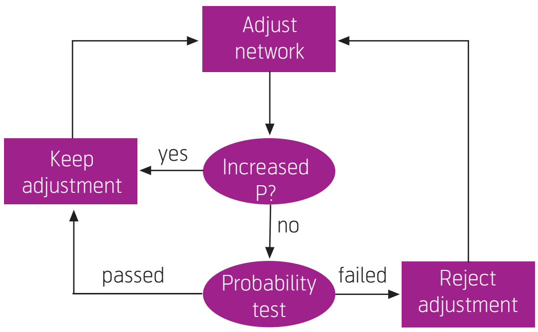

Figure 5 The Metropolis algorithm. Any changes which increase profits are accepted. A randomly chosen fraction of changes which decrease profits are accepted. This fraction depends on the size of the decrease and on the parameter T

To overcome this difficulty the simulated annealing algorithm was developed. The insight which led to this algorithm was the idea that the route from some initial state of the system to the optimal state will need to include steps which reduce the profit as well as steps which increase the profit. The question then is how to balance steps which reduce profit against those which increase it. The Metropolis algorithm outlined in Figure 5 gives a recipe for deciding whether a change in the state of the system should be accepted or rejected.[13] Changes which increase profits are always accepted. Changes which decrease profits are accepted with probability $\exp(-\Delta P / T)$. The parameter T determines the size of increases which are to be accepted: a profit decrease of size T has an acceptance probability of roughly one third.

The performance of the algorithm depends on the choice of adjustments made and the variation in T made during the annealing. Furthermore it is impossible to be sure that the final answer gives the largest profit possible. The problem is that there are many local maxima in the profit – states which have higher profits than all the states which can be reached by a small number of adjustments but which do not give the largest profit possible. It is very easy for the system to be trapped in one of these local minima if the parameter T is too low to permit the system to escape. In practice the only safeguards against this happening are to reduce T as slowly as possible (within the time constraints) and to restart the simulation and see if it finishes in the same state.

The adjustments made to the system are shown in Figures 6a and 6b. These differ slightly for the two deployment scenarios (existing and new network operator respectively) discussed below. Figure 6a shows the adjustments made for the first scenario, that of an established DSL provider. Exchanges and their surrounding postcodes can be upgraded to fibre; exchanges can also be decommissioned in which case their postcodes must be upgraded to fibre and connected to the nearest fibre exchange. Figure 6b shows the adjustments made in the second scenario. An exchange can be upgraded to fibre along with its surrounding postcodes (this implies some sort of agreement between the company owning the DSL network and the new service provider). A single postcode can be upgraded to fibre and connected to the nearest upgraded exchange. Note that when upgrading an exchange it is not strictly necessary to upgrade all

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[13] *Metropolis, N, Rosenbluth, A, Rosenbluth, M, Teller, A, and Teller, E. 1953, Journal of Chemical Physics, vol 21, pp 1087-92. Press, W H, Teukolsky, S A, Vetterling, W T, and Flannery, B P. 1992. Numerical Recipes, Cambridge University Press.*

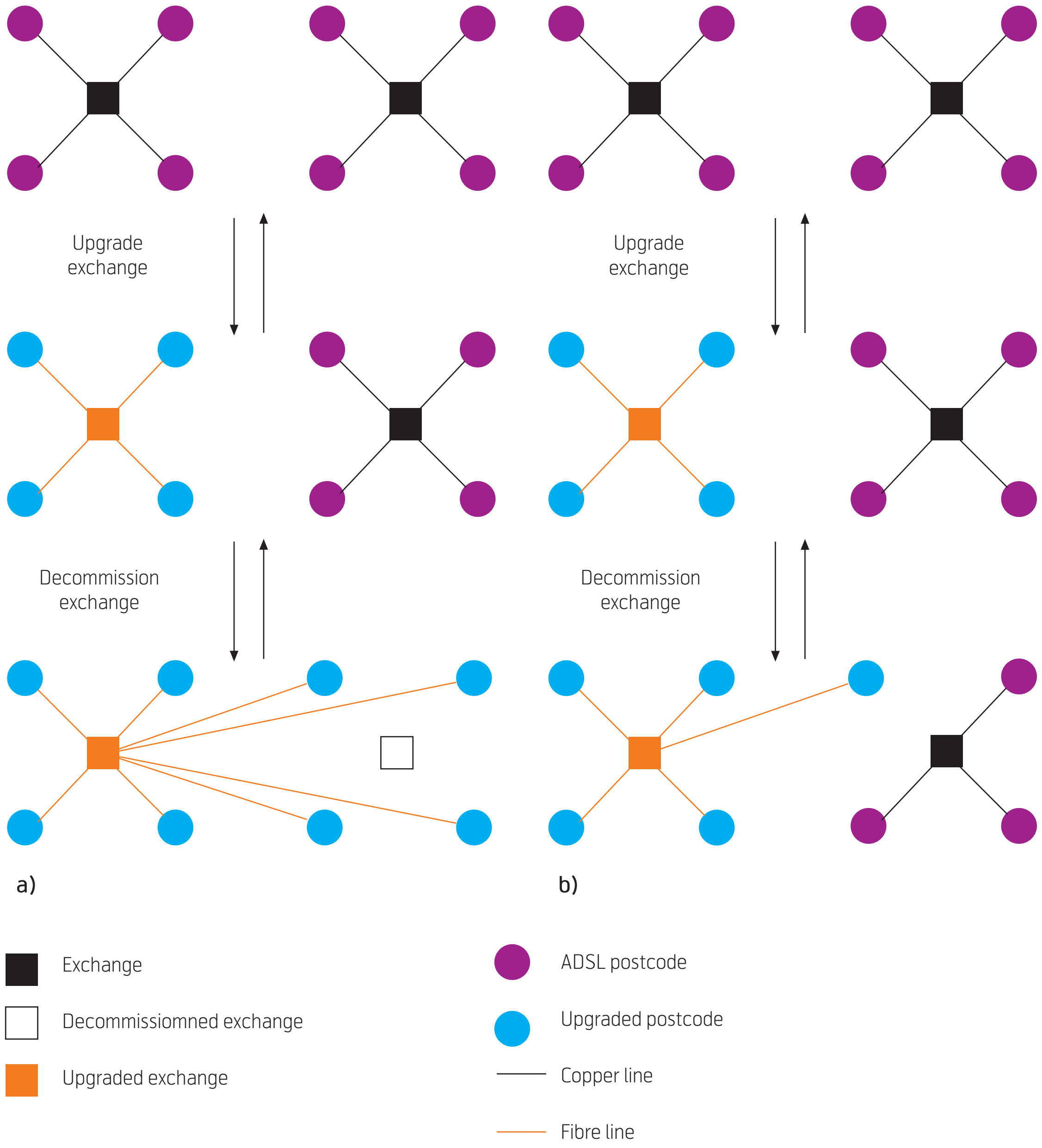


Figure 6 a) Adjustments made to the network of an established supplier; b) Adjustments made to the network of a new supplier

the surrounding postcodes to fibre, this is simply convenient. As well as the adjustments described above the algorithm also performs their reverse: restoring postcodes and exchanges to DSL, and re-commissioning decommissioned exchanges.

It should also be mentioned that, in these simulations, maximum effective range of fibre-optic cable is set at 30 kilometres. This is implemented within the algorithm by artificially reducing the profits of any network segment exceeding this distance by a number large enough to ensure that this network segment is always rejected by the algorithm.

2.3 Parameter Values and a Case Study

We apply the methodology described above to a test case: the Isle of Wight, UK. The Isle of Wight is a good test case since it is a self-contained entity with its own local network and well defined boundaries. Furthermore, it has a mixture of densely populated urban areas and sparsely populated agricultural land, making it a microcosmic reflection of the UK as a whole. The methodology is applicable to the whole of the UK or any other country, and we hope that in a further study we will be able to demonstrate results for that.

Initial input parameters (Table 1) derive from a number of industry sources and were formed as an average from communications with various expert groups. Values are representative of optical fibre deployments in Western Europe and North America. For different case studies, parameters could be changed to value applicable to other market conditions.

Parameter	Description	Old network	New network	Units
n	Run time of investment period			years
O^{ex}_{dsl}	Operating cost of DSL exchange	200	0	USD in thousands
O^{ex}_{fb}	Operating cost of fibre exchange	182	200	USD in thousands
C^{ex}_{ug}	Cost of exchange upgrade	150	0	USD in thousands
C^{ex}_{inst}	Cost of installation of new exchange	0	370	USD in thousands
C^{hh}_{ug}	Cost of household upgrade/installation	200	200	USD
C_{dig}	Cost of trenching / cost of blowing cable	50/20	50/20	USD per metre
C_{cable}	Cost of fibre cable	1.5	1.5	USD per metre
–	Ratio digging and blowing	60:40	100:0	
–	PON split ratio	1:32	1:32	
r_{dsl}	Revenue from DSL broadband subscription (ARPU)	40	40	per household per month
r_{fb}	Revenue from optical fibre broadband service (ARPU)	55	55	per household per month

Table 1 Input parameters for Test Case: Isle of Wight

We consider the problem of deploying a fibre optic network from two perspectives. The first is that of a company already owning and operating a network. This company can make savings from decommissioning exchanges and from upgrading exchanges. A modest increase in the subscription fees and thus ARPU is also possible. We have left ARPU for DSL and fibre services constant over the period of investment. As the operator keeps innovating, new capacity demanding services and applications will be implemented which will stop the ARPU decreasing.

The second perspective is that of a new company wanting to deploy a new optical fibre network. This company cannot make savings from upgrading or decommissioning infrastructure since it does not possess any. However it can, relatively speaking, generate additional revenues, since its business case builds on subscription fees for current broadband services and new services that cannot be delivered over copper infrastructure.

No matter whether new or existing network operator, both have to maintain communication outside the access network. We here assume that both either have or, in the case of the new operator, will build out their own transport network. Many ISPs also lease part of the incumbent's network for this purpose. In our scenario, the operational cost and installation cost of the transport network are shared in equal portions among all exchanges in operation. For ease of reference, one could single out costs associated with the transport network into separate modelling variables.

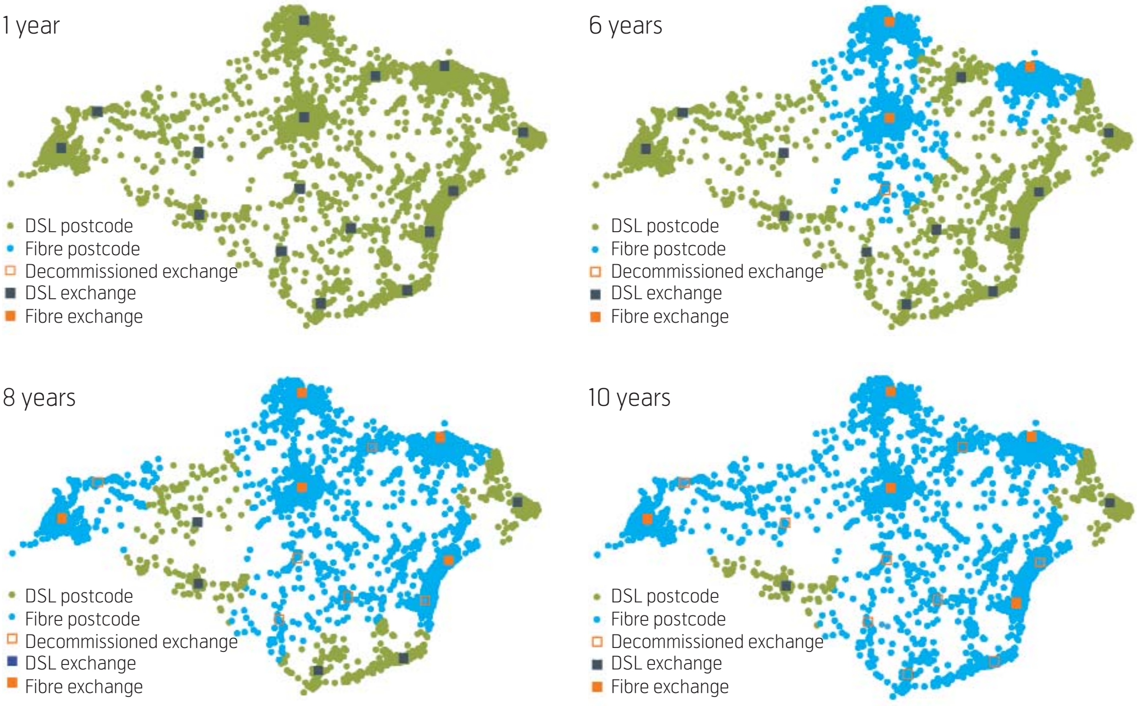
Over the last decade competition in the European telecommunication industry has significantly increased. The broadband sector, in particular, has been hit by a wave of local loop unbundling regulations and wholesale agreements that have eased the entrance of alternative providers. In the course of operation, all providers gain and lose subscribers to competing offers. Some subscriber loss is normal, too much is unhealthy. Because of the high investment required, far fewer broadband providers will roll-out optical fibre networks than there are DSL providers. And those who dare will refrain from a roll-out in the same areas where optical fibre has already been rolled out by others to avoid competing head on. In the short- and medium term, optical fibre roll-outs will reduce service competition, resulting in reduced subscriber churn. There is only one way to go for subscribers: from ADSL to optical fibre. If the new fibre services are attractive, the adoption rate should mirror that of ADSL broadband. This is the case we modelled. All current households with broadband will migrate if fibre has been rolled out in the area. Within the optimisation, it is however feasible to set the adoption parameter to a lower rate.

2.3.1 Established DSL Provider

Figure 7 shows the optimal network for the first of the cases just described: that of an established provider which targets to upgrade some (or all) of its network to optical fibre. The figures concern a number of investment scenarios in which profits are maximised over n years, depending on the length of the investment period. They should however not be mistaken for a time series. Results highlight that profits must be maximised over a period of at least six years or greater for an upgraded network to increase profits over those generated by the legacy. The longer a network operator is willing to wait, the larger and more extensive the fibre deployment will be, and the larger the long-term profits the network will generate.

There will also be considerable variation of deployment cost across length of different business plans – between USD 920 per home passed (year 6) and USD 870 (year 9). With longer investment periods prevailing, more homes can be upgraded that require higher connection costs. However, economics of scale work well at the level of homes passed, and deployment cost comes down as deployment spreads (Table 2).

Investment periods differ across Western Europe. Nordic utility companies that have traditionally applied long-term investment strategies for electricity and gas grids have successfully applied these strategies to a number of local FTTH deployments. Such long-term vision would serve the population better. More households could be connected and the potential risk of digital exclusion areas minimised. In the case of the Isle of Wight, 88 % coverage could be achieved in year 9, compared to just over 51 % in year 6. In contrast, and mainly due to market expectations, incumbent telecom providers operate under much shorter investment strategies that very rarely exceed five years. The consequences of such an approach to optical fibre deployments would be a much lower coverage, extending exclusively into densely populated areas.



1 year

6 years

8 years

10 years

Figure 7 Spatial fibre deployment scenarios for established DSL provider, with different investment periods

Time (yrs)	1	2	3	4	5	6	7	8	9	10
Exchanges										
n^{ex}_{dc}	0	0	0	0	0	1	2	6	7	9
n^{ex}_{dsl}	16	16	16	16	16	12	10	5	4	2
n^{ex}_{fb}	0	0	0	0	0	3	4	5	5	5
Households (in thousands)										
n^{hh}_{dsl}	62.80	62.80	62.80	62.80	62.80	31.00	23.50	10.70	7.10	5.10
n^{hh}_{fb}	0.00	0.00	0.00	0.00	0.00	31.80	39.30	52.00	55.70	57.70
Subscribers (in thousands)										
n^{bb}_{dsl}	23.80	23.80	23.80	23.80	23.80	11.20	8.40	3.80	2.50	1.80
n^{bb}_{fb}	0.00	0.00	0.00	0.00	0.00	12.50	15.40	20.00	21.30	22.00
Finance (annually, in million USD)										
P	8.20	8.20	8.20	8.20	8.20	8.35	8.73	9.09	9.58	9.98
E	3.20	3.20	3.20	3.20	3.20	5.32	5.46	5.93	5.68	5.40
R	11.40	11.40	11.40	11.40	11.40	13.68	14.19	15.01	15.26	15.38

Table 2 Established DSL Provider: results of various investment scenarios

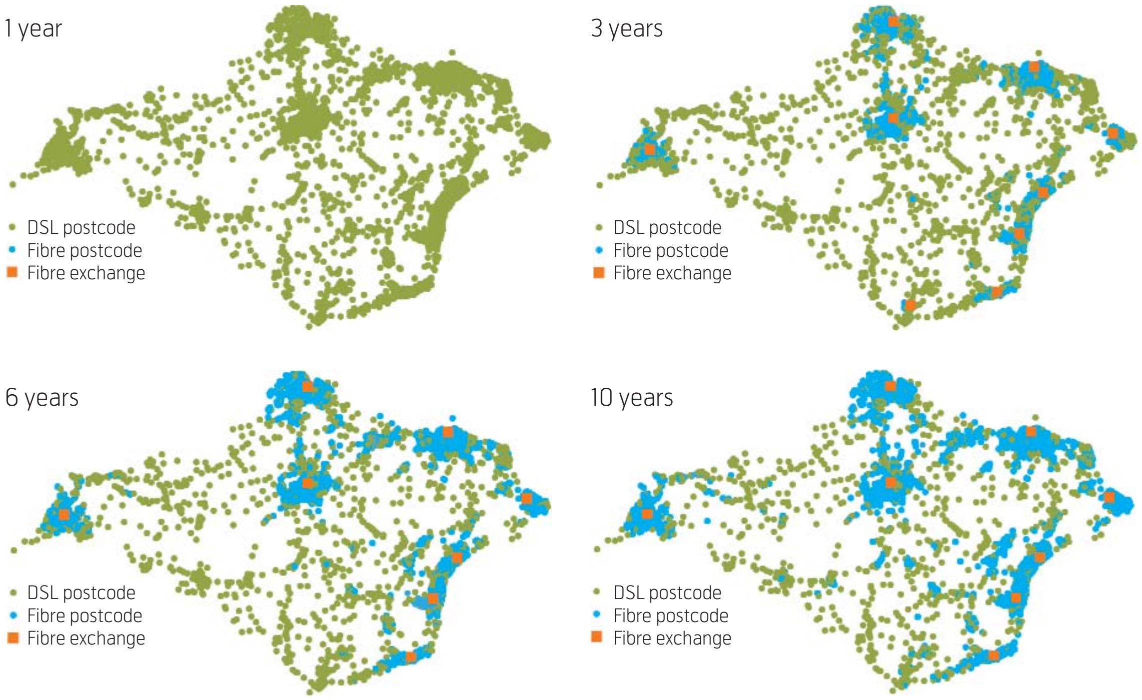


Figure 8 Spatial fibre deployment scenarios for new provider, with different investment periods

Time (yrs)	1	2	3	4	5	6	7	8	9	10
Exchanges										
n_{dc}^{ex}	0	0	0	0	0	0	0	0	0	0
n_{dsl}^{ex}	0	0	0	0	0	0	0	0	0	0
n_{fb}^{ex}	0	0	9	9	9	8	9	9	8	8
Households (in thousands)										
n_{dsl}^{hh}	62.80	62.80	17.20	12.60	10.30	9.10	7.00	6.20	5.70	4.90
n_{fb}^{hh}	0.00	0.00	45.60	50.20	52.50	53.70	55.80	56.60	57.10	57.90
Subscribers (in thousands)										
n_{dsl}^{bb}	23.80	23.80	6.20	4.40	3.60	3.10	2.40	2.00	1.90	1.60
n_{fb}^{bb}	0.00	0.00	17.60	19.40	20.20	20.70	21.40	21.80	21.90	22.20
Finance (annually, in million USD)										
P	0.00	0.00	2.63	4.68	6.04	7.20	7.80	8.40	9.03	9.44
E	0.00	0.00	9.03	8.13	7.32	6.45	6.36	5.96	5.44	5.22
R	0.00	0.00	11.63	12.78	13.36	13.65	14.16	14.36	14.48	14.66

Table 3 New service provider: results of various investment scenarios

Figure 8 shows the optimal network for the second scenario: a new provider starting fibre-optic deployment. The simulations suggest that an investment period of three years is sufficient to move the deployment forward and of connecting about 72 % of all homes on the island. A long investment period would increase service penetration to 90 % in year 8. Deployment then stalls at that level. The remaining 10 % of homes will not be connected. The same applies to a small percentage of DSL subscribers served over the copper network of a competing provider. The location of this fraction of the population in low density areas increases the connection cost beyond a point that is profitable. In this respect, the two deployment scenarios are very similar in putting a new digital divide at 10 % of homes on the island (Table 3).

The deployment costs per homes passed are considerably higher than for an established operator in short investment periods – about USD 1980 in year 3. The input parameters have been set so that they reflect that no duct-sharing and co-location agreement exist between the incumbent and new operator. Therefore the new operator has to build out a new set of central offices and duct systems, increasing overall civil engineering cost. Theoretical trenching costs are here assumed to be at least 40 % higher for a new operator. In long-term investment scenarios of seven to nine years, deployment cost in the two scenarios stabilise around USD 900 per home connected for both old and new operator, despite the initial handicap.

In this idealised scenario of a new deployment we assume that the optic-fibre service holds a high degree of attraction. All existing DSL subscribers will be migrating *en mass* to the new fibre services, once the service becomes available. If the old network service provider is late in upgrading and in offering comparable services, this is a likely outcome. If the old network provider upgrades, competition at the infrastructure-level will ensue, resulting in a much lower subscriber churn rate from the old to the new provider. Hitting the positive profit period will also draw out to well over the initially simulated three years, closing the gap between the deployment periods of old and new providers.

3 Conclusion

We have demonstrated a method for optimising the upgrade of broadband infrastructure which takes account of the costs and potential revenue, the spatial distribution of exchanges and customers and the time investors are willing to wait for a return on their investment. Our work not only demonstrates the feasibility of this method, but also that upgrading the network to fibre optic cable can be a sound investment. The parameters used with this method can be altered to reflect different business, regulatory and geographical environments, making the overall method applicable and valuable to a large number of real world business cases that consider fibre-optic deployment.

To illustrate the versatility of our method we have looked at installing a fibre-optic network from two very different perspectives. The first is that of an established Internet service provider which already owns a profitable copper-DSL network. Such companies experience a significant entry barrier to providing fibre-optic services in that the legacy network will not just generate revenue, but expenses on top of new expenses incurred when deploying a fibre-optic network. Lower operating cost for optic-fibre exchanges do not off-set this imbalance in the short-term, but possibly in the long-term.

The second perspective is that of a new network operator building a completely new infrastructure. The deployment cost will be higher for such a company since we assume that no duct-sharing agreement exists with incumbents that could substantially save on civil engineering costs. On the positive side, the new provider can choose where to build its infrastructure to supply areas with the largest numbers of potential customers, meaning that it can assure itself of a larger return per length of fibre-optic cable deployed. The simulation would favour the building of new network, rather than upgrades.

In the world of web 2.0+, new service providers have shown propensity of quickly eroding existing market dominance through offering innovative services. However, for fixed-line services, optic-fibre deployment costs that would eventually allow service innovation at a much higher level than previously possible set a high entry barrier to new market entry. Our spatial cost simulations highlight that it is feasible to reduce such costs and to ease market entry, taking into account the geographical and socio-economic environment of potential deployment areas.

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