Development of FIDO - A Network Design Tool for Fibre Cable Layout

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Abstract

There are currently a number of new fibre optic cable networks being laid through New Zealand's major cities. This paper discusses a design tool, termed FIDO (Fibre Diversity Optimiser), that has been developed for a network operator to assist them in their network planning. FIDO combines a specialised visualisation GUI with a mix of optimisation and heuristic procedures to create a customised decision support tool for fibre cable layout. FIDO is currently being used by the operator's design team.

1 Introduction

In February 2000, it was announced that a new telecommunications company, TelstraSaturn, was being formed through the merger of Saturn Communications and the NZ division of Telstra. Telstra is the well-known Australian telecommunications operator with a world wide revenue of $A19 billion and the backing of a 51% shareholding held by the Australian government. Saturn Communications began life as the Kiwi Cable Company Limited, a small cable and satellite TV operator based on the Kapiti Coast near Wellington. Now owned by Austra in Australia, Saturn is best known for their successful rollout of a fibre optic cable network through suburban Wellington where they spent $250 million laying 1,300 kilometres of network passing 120,000 homes. Bundling telephony and cable TV operations allows Saturn to compete successfully with the incumbent operator Telecom.

The press release detailing the creation of TelstraSaturn included the announcement that the new company had a 5 year budget of $1.2 billion to construct a new broadband network passing 65 per cent of NZ homes and 80 per cent of NZ businesses in NZ’s five major cities. Unlike the existing Telecom network, this new network is designed to carry the full range of telephone, data, Internet, mobile and cable and satellite TV services.

By the end of 2000, Aucklanders were witnessing extensive trenching work throughout the central business district (Figure 1) as TelstraSaturn rolled out the first stages of their new network. A $200 million network in Christchurch is now also under construction and the first part of the network was activated on March 1, 2001. Plans for networking greater Auckland are also well underway.

Figure 1: The Auckland CBD was subject to extensive digging operations as TelstraSaturn and other operators laid ducts to carry their new fibre optic networks. Source: NZ Herald.

TelstraSaturn also announced that it would lay a fibre optic submarine cable running from Auckland via Wellington to Christchurch. This cable has now been completed at a cost of around $100 million. The new cable bypasses existing infrastructure owned by Telecom and Clear to give a 5-fold increase in main trunk capacity. It uses 750 kilometres of cable buried on the sea floor and another 250 kilometres of landbuild to connect New Zealand's three major cities Auckland, Wellington and Christchurch.

Through collaboration between the Operations Research (OR) Group at Auckland University (see [2], [3]) and staff previously at Telecom, a key TelstraSaturn manager was aware of mathematical optimization techniques, and approached the OR Group for assistance in designing their network. This paper describes the development of the software system FIDO that is now being used by TelstraSaturn to design their Auckland, Wellington and Christchurch networks.

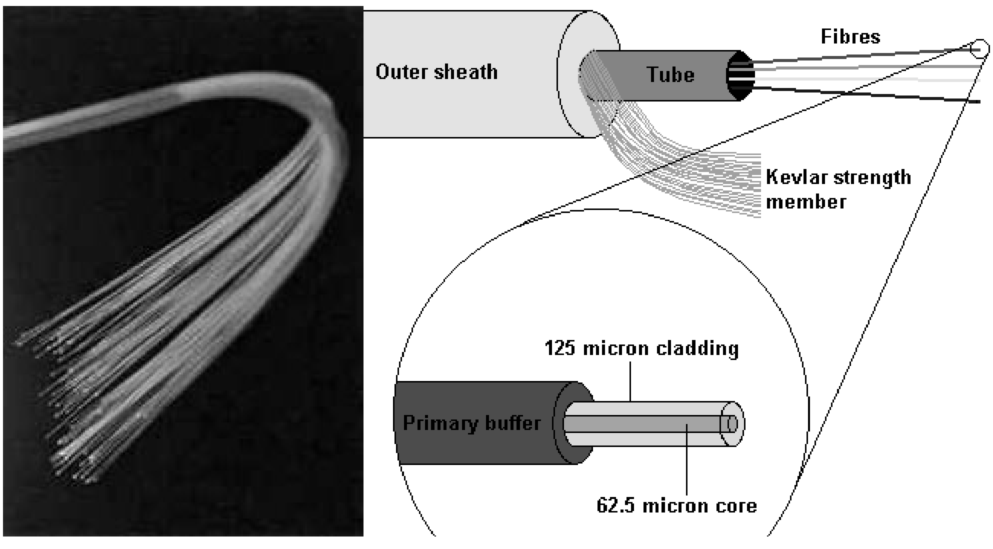

Figure 2: Fibre optic cables (left) and a schematic of their construction. Images from DataCottage.com and NewScientistJobs.com

Network Design

The basic objective of the TelstraSaturn networks is to provide a pair of fibre optic cables, similar to those shown in Figure 2, joining a customer's premises to a TelstraSaturn exchange. (A pair of fibres is required as each fibre carries data in only one direction.) The TelstraSaturn network is unusual in that each customer site is connected to the exchange by two fibre pairs, only one of which is in use at any time. By ensuring that these two fibre pairs use different paths to connect with the exchange, TelstraSaturn can provide a *diverse* service, meaning that if the fibre pair being used is accidentally cut, switching equipment in the customer's building and the exchange can immediately start using the second unbroken fibre pair without disrupting transmission.

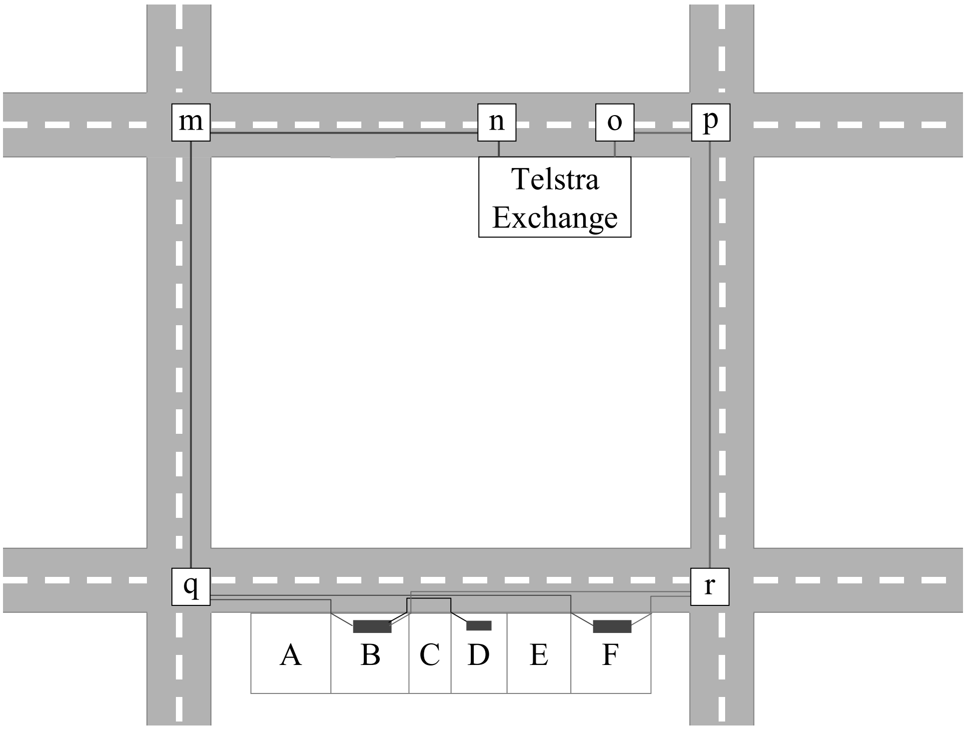

Figure 3: A sample network that feeds customer buildings B, D and F in a street. The street is connected to the exchange by two feeders, one following a feeder path from vault *q* through vault *m* to the exchange entry point *n*, and the other following a path from vault *r* though vault *p* to entry point *o*.

Figure 3 shows a network that might be built to serve customers in 3 buildings, denoted B, D and F, on one side of a street. (The other buildings do not have connections with TelstraSaturn.) Firstly, we note that the street is connected to the exchange by fibre optic cables running from vaults *q* and *r* located at opposite ends of the street. These cables, termed *feeders*, are laid in feeder ducts within trenches in the roads. The two feeder paths used to connect vaults *q* and *r* to the exchange are strictly disjoint in that they never share any vaults or roads. This ensures there is a diverse service delivered to the street that will not be disrupted even if the fibre cables in some road are accidentally cut.

Each feeder cable must be chosen from a set of fixed sizes ranging from 24 to 144 fibre pairs. Feeder cables may be joined in vaults using a welding process. Referring again to our example, we may have a 24 pair feeder running from vaults *q* to *m*, which is welded, along with some other 24 fibre pair feeder (not shown), into a 48 pair cable running from vault *m* to *n*. As usual, the larger sized cables are cheaper per fibre pair than the smaller ones.

Buildings B and F within the street obtain a diverse service by being connected to the vaults at either end of the street. Each of these buildings contains a TelstraSaturn-owned multiplexer that is connected to each of the two vaults, typically via a single fibre optic pair. These fibre pairs are welded into the larger feeder cables within the vault, thus providing two physically continuous fibre pair connections from the exchange to the multiplexer. We can consider each building to belong to a fibre pair ring, in this case given by vaults *n*, *m*, *q*, *r*, *p*, *o*. This is a ‘thinning ring’ in the sense that the fibre counts of the cables in this ring reduce with increasing distance from the exchange.

The multiplexer in each building is responsible for managing the data being exchanged with the building’s users and generating the optical signals to transmit (and receive) this data over whichever of the two optical fibre pairs is currently in use. This multiplexer also ensures diversity by automatically switching to the alternate fibre pair in the event of the currently used pair failing for some reason.

The fibre pairs connecting the building multiplexers to the *q* and *r* vaults run in street ducts. These ducts differ from the feeder ducts in that they include spurs used to carry the fibre to the buildings. Notice that to preserve diversity, two different spur ducts, one on either side of the building, are used to connect each building.

Building D in this example is not a high-speed data user, but instead has requested a low speed copper-wire connection. Rather than running copper back to the exchange, TelstraSaturn provides a copper connection to a building by feeding it off one of their multiplexers located within some other building in the street. In this case, a copper wire is run within the street ducting from the multiplexer in building B through to building D. The multiplexer handles the combining of two (or more) data streams into a single data stream for transmission, and the demultiplexing of received data back into separate data streams.

We note that the network design outlined above is *fibre rich* in the sense that each building is physically connected to the exchange by two continuous fibre pairs. This is in contrast to conventional fibre optic network layouts where multiplexers are used to combine the data streams from many buildings into a single fibre pair, which itself may be further multiplexed with data streams from other fibre pairs before the signal reaches the exchange. TelstraSaturn initially considered a SONET-ring architecture (see [1]) based on a set of interlinked rings containing add-drop multiplexers, but then settled on a thinning ring architecture to reduce the number of multiplexers required. This choice of architecture makes sense for dense networks in which the cost of fibre is small compared with multiplexer costs.

There are a number of optimisation problems that need to be solved to minimise the total cost of the network that is built. To discuss these, we will assume, as was the case in our work, that TelstraSaturn have specified which buildings are to be served with fibre optic connections, which buildings are to receive copper connections, and the number of fibres (or copper pairs) required by each building. (Although our approach assumes perfect foresight, and raises some interesting questions about how to produce a network that hedges against uncertainty in demand, we shall ignore these issues in this paper.) Each building belongs to a street, where a street here means a road segment with vaults at either end. The demand for fibre in each street comes from the requirements for fibre and copper connections to the buildings in the street. The exact level of this demand for each street is determined by solving an optimisation problem called the *street optimisation*.

As well as specifying which streets were to be allocated fibre, TelstraSaturn also specified which roads were going to be trenched to contain feeders. As far as this paper is concerned, the cost of this trenching is fixed, and so we focus on the costs associated with the purchase and laying of cable. Much of this cost comes from running diverse feeder cables to the streets. The problem of determining the paths these feeders will take is called the *(feeder) path optimisation* problem.

Finally given the fibre requirements and feeder paths for each street we seek an allocation of cables and welds to the feeder paths that minimises the overall cost of cable. We call this the *cable optimisation*. The three optimisation problems we consider are in fact parts of a large integrated design problem. For this application we solve them separately using a mixture of optimisation and heuristics. We shall now discuss each problem in turn.

Path Optimisation

The feeder path optimisation problem is to find two diverse paths of minimal total length that connect the vaults at either end of a street to the exchange. To represent this, we can form a graph in which each arc corresponds to a road segment that is being trenched for feeders, and each node corresponds to a vault. This gives us a graph G=(V,A) where A designates the feeder arcs, and V the associated vaults. Each feeder arc a has a length c(a), which can be used to generate a dollar cost associated with the laying of any of the available cable sizes down the road.

We assume that each network contains just a single exchange. We represent this in the graph as two nodes, v_1 and v_2, being the two feeder entry points for the exchange.

Consider some street running between vaults $p\in$V and $q\in$V. We wish to provide this street with two feeder paths on G that are node and arc disjoint and connect p and q to the exchange nodes v_1 and v_2. We wish the sum of the lengths of these paths to be minimised. Our experience is that using such paths for each street leads to low overall cabling costs.

An optimal solution to this problem can be obtained for each street by solving a minimum cost network flow problem. This network flow problem uses a directed network that is constructed from the feeder network G as follows. The street's vault nodes p and q are given a supply of 1 unit each which is matched by demands of 1 unit at each of the exchange nodes v_1 and v_2. All other nodes have demand 0. Feeder arc (p,q), if it exists, is deleted from the network. Each remaining feeder arc (r,s)$\in$A is replaced by two directed arcs (r,s) and (s,r), each with capacity 1 and a cost equal to $c(r,s)$, the length of the original feeder arc (r,s). To ensure node diversity, we follow the standard approach of splitting each node i into two nodes, i^+ and i^-, which are then joined by a directed arc (i^+, i^-) with cost 0 and capacity 1. All arcs going into node i are redirected to node i^+, while all arcs leaving node i are modified to now leave node i^-. Solving for the least cost flow on this network gives unit flows in those arcs that define the desired feeder paths for street (p,q).

This approach minimises the cost for each street in isolation. However, typically a feeder arc will be used in the paths for many different streets. This suggests that the paths for the streets should be chosen to ensure the number of fibre pairs in each feeder arc pack efficiently into the available cable sizes. (We discuss below why this is a packing problem.) We experimented with a local search approach that re-solved the paths for each street using marginal fibre costs for the feeder arcs calculated assuming the paths for the other streets were fixed. While this gave some small improvement, TelstraSaturn did not deem this issue to be of high priority and so it has been left for subsequent work.

Figure 4 shows a screen shot from the FIDO program. This program provides access to the various optimisation engines and tools for visualising the network design that is produced. In this figure, a single street has been selected, and FIDO has displayed the buildings associated with the street and the minimum-length paths connecting this street to the exchange.

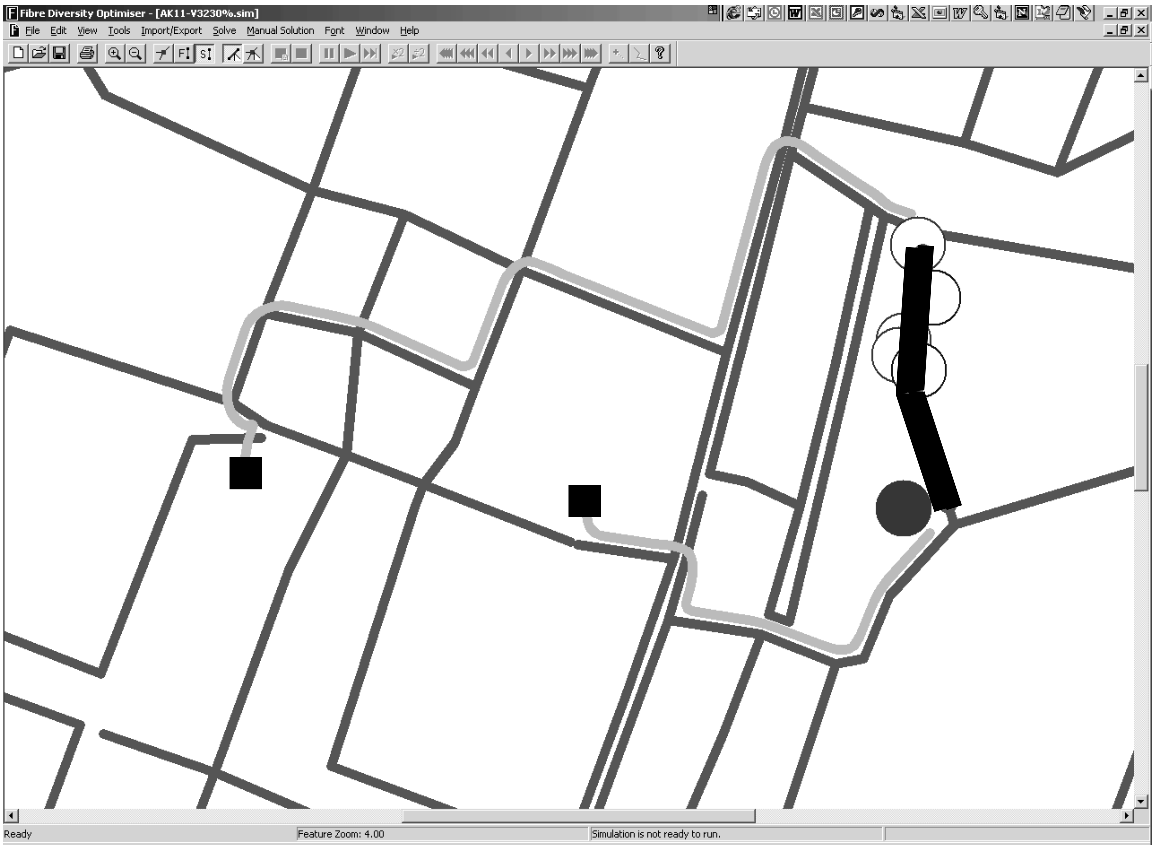

Figure 4: This figure shows the paths from a single street (highlighted) back to the exchange fibre entry points (shown by square nodes). Buildings are shown as circles, where a hollow building indicates that it does not contain a multiplexer (see below).

Street Optimisation

A key parameter in the optimisation of the fibre network is the demand for fibre in each street, as this will determine how the paths back to the exchange are combined into cable sizes. The buildings in any given street have a mixture of telecommunication services that they require ranging from POTS (plain old telephone services) to high speed data services in dedicated fibre. As shown in Figure 3 the POTS service to a building requires a multiplexer to be installed (in a possibly different building) from which copper cable is ducted to the telephone receivers. To make management of the network easier, each customer building's copper demand must be served by a single multiplexer.

In locating and sizing multiplexers in a street there is a trade off between using fibre and multiplexers as opposed to using copper. For example, if POTS was all that was required one could install a single multiplexer and then lay copper cable in a star network connecting all telephones in the street to this multiplexer. Alternatively, one could save on copper cost by installing a multiplexer in every building.

The optimum mix of copper and fibre is determined in FIDO by solving a set-partitioning problem of the form

$$\begin{aligned} \text{minimise} \quad & c^T x \\ \text{subject to} \quad & Ax = e, \\ & x_j = 0,1, \end{aligned}$$

where e is a vector of 1's corresponding to each customer building in the street. Each column j of the matrix A corresponds to a particular multiplexer size and location, and a set of buildings that connect to it using copper cable. The zero-one variable x_j indicates whether to install the multiplexer. The cost c_j of this choice is a function of the multiplexer size, the amount of copper demand that it serves, the location of this demand, and the location of the street relative to the exchanges.

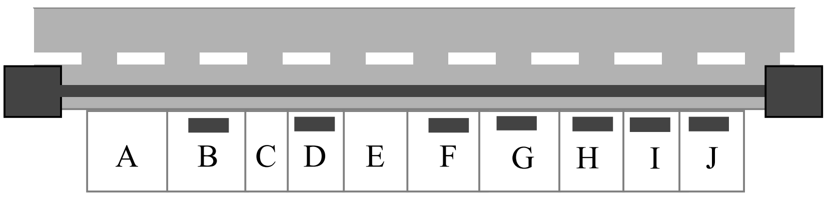

Figure 5: A street containing customer buildings B, D and F, G, H, I, and J.

As an example consider the street containing seven customer buildings shown in Figure 5. For this street suppose all customer buildings require 100 units of copper service only, and multiplexers come in discrete sizes of 500 and 1000 copper circuits, with costs C_{500} and C_{1000} respectively. One possibility is to install a single large multiplexer in building F and serve all customers, including itself. This would correspond to a column of A, $a_j=[1\ 1\ 1\ 1\ 1\ 1\ 1]^T$ with a cost

$c_j =$ C_{1000} + cost of copper from F to B, D, G, H, I, J + cost of 2 diverse fibre pairs from exchange to F

Note that we are assuming the feeder paths for this street have been determined, and so the length of fibre required to run two diverse fibre pairs to a particular building can be computed, and the cost then estimated from this.

An alternative is to install a small multiplexer in building D serving B and itself and a small multiplexer in building H serving the other customers This would correspond to two columns, $a_j= [1\ 1\ 0\ 0\ 0\ 0\ 0]^T$ with a cost

$c_j =$ C_{500} + cost of copper from D to B + cost of 2 diverse fibre pairs from exchange to D and $a_j = [0\ 0\ 1\ 1\ 1\ 1\ 1]^T$ with a cost

$c_j =$ C_{500} + cost of copper from H to F, G, I, J + cost of 2 diverse fibre pairs from exchange to H.

To assist in maintaining the network, TelstraSaturn required that the buildings connected to a particular multiplexer should be contiguous. This makes the set partitioning problem a lot sizing problem, which can be solved for each street using dynamic programming.

As we noted, the fibre cost depends on the lengths of the feeder paths that the fibre takes from each vault back to the exchange. This is provided by the path optimisation for each street as discussed in the previous section. For streets far from the exchanges the fibre cost will be high and so the optimisation will prefer fewer multiplexers and more copper, whereas for streets close to the exchanges, the fibre cost will be relatively low, and so more small multiplexers might be preferred to avoid high copper costs.

Cable Optimisation

Once the paths for the streets have been calculated, and the fibre count for each path determined by the street optimisation, we need to determine how the fibre pairs will be packed into feeder cables. There are a number of important factors to consider. As we mentioned before, we can use welding at a vault to connect two or more small cables to a single larger cable, such as maybe two 24's into a 48, or three 24's into a 96. While the larger cable sizes are cheaper per fibre pair, there are significant costs associated with each weld that need to be taken into account. As well as welding smaller cables onto larger ones, it is also possible to partially cut a cable at some point along its length, and weld fibres into the middle of the cable. This is useful when 'dropping' fibres onto a street from a large cable that passes through a vault. Figure 6 shows examples of these weld types. For system maintenance reasons, TelstraSaturn specifies that once a set of fibres have been grouped together in a cable, they should never be split apart again. This means that if we have two 96-pair cables, each of which is only 75% used (i.e. only 48 of their fibres are being used), then these cannot both be welded into a 144-pair cable. TelstraSaturn also specified that because fibre pairs are grouped into tubes of 12 pairs each within a cable, all welds needed to be in multiples of 12 fibre pairs.

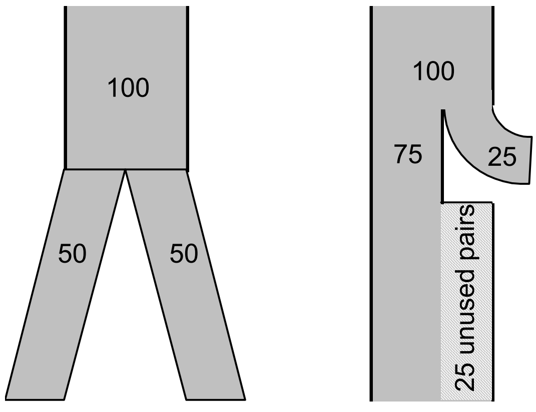

Figure 6: Examples of a join weld (left) and a drop weld (right) used for feeding a street. The figures show the number of fibre pairs involved.

A greedy heuristic procedure was developed for determining where welds should occur, and what mix of cable sizes should be run within each feeder duct. This heuristic begins by working from the streets back up to the exchange determining where cables should be joined. It then uses a first-fit-decreasing bin-packing heuristic to pack the street fibres and incoming cables into typically larger cables. This has proven effective for this problem. The FIDO screen shot in Figure 7 shows the cables that are used to feed the street highlighted in Figure 4.

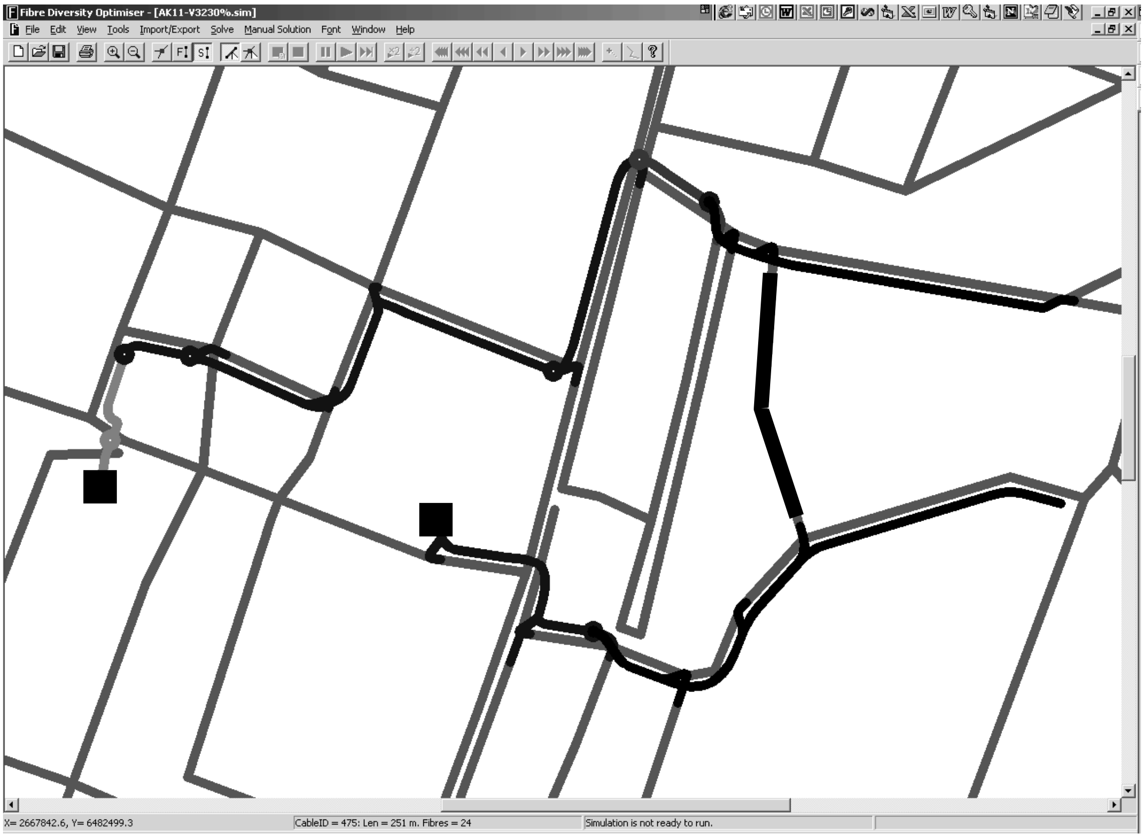

Figure 7: This figure shows the cables that are used to feed the highlighted street. The size of the cables increase as the cables get closer to the exchange. Note that the street is connected to its two feeder cables using drop welds.

Conclusions

FIDO has now been used to assist in the network planning for the Auckland, Christchurch and Wellington central business districts, and is currently being used to plan the Auckland suburban network. The highly dynamic nature of TelstraSaturn's architecture design process meant that FIDO had to be immensely flexible to move with the continually evolving problem specification. The success of this product depends as much on its flexibility and built-in visualisation capabilities as on the optimisation and heuristic algorithms it contains. There are a number of very interesting optimisation problems arising from this work that could not be fully modelled in the time available. (A number of these problems emerged on December 24, 2000 with solution code required for delivery on December 26!) Developing appropriate optimisation algorithms for the new thinning ring architecture favoured by TelstraSaturn continues to be an active area of our research and development effort.

Acknowledgments

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