Energy-Efficient Design and Optimization of Wireline Access Networks

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Abstract—Access networks, in particular, Digital Subscriber Line (DSL) equipment, are a significant source of energy consumption for wireline operators. Replacing large monolithic DSLAMs with smaller remote DSLAM units closer to customers can reduce the energy consumption as well as increase the reach of the access network. This paper attempts to formalize the design and optimization of the “last mile” wireline access network with energy as one of the costs to be minimized. In particular, the placement of remote DSLAM units needs to be optimized. We propose solutions for two scenarios. For the scenario where an existing all-copper network from the central office to the customers is to be transformed into a fiber-copper network with remote DSLAM units, we present efficient polynomial-time solutions. For the green-field scenario, where both the access network layout and the placement of remote DSLAM units must be determined, we show that this problem is NP-complete. We present an optimal ILP formulation and also design an efficient heuristic-based approach to build a power and cost optimized access network. Our heuristic-based approach yields results that are very close to optimal. We show how the power consumption of the access network can be reduced by carefully planning the access network and introducing remote DSLAM units.

I. INTRODUCTION

Energy-related expenses have become a major concern for network operators. These expenses are especially severe in emerging economies, given a lack of access to reliable grid power, high ambient temperatures, and the high cost of using and maintaining power backups such as diesel generators.

In current DSL access networks, an individual copper loop is placed between each customer and the nearest access node site, which houses the DSLAM. The power level for driving such a copper line primarily depends on the user-requested bit-rate and the loop length of the DSL. Therefore, reducing the loop length will bring down the power consumption of the DSLAM equipment and this can be achieved by placing DSLAM units closer to customers and connect them to access node through fiber.

Remote DSLAMs are currently used by operators to increase the reach of their access node to additional customers without compromising on data rates. In contrast to large, monolithic DSLAMs, the smaller remote DSLAM units don’t need any real-estate (can be mounted on a roadside pole or in customer’s basement) or active cooling (air conditioning). According to our measurements (carried out in a typical metropolitan area of India), monolithic DSLAMs dominate the equipment energy consumption in access node sites contributing to as much as 80% of it. Moreover, DSL line driver has been shown to contribute close to 50% of the energy consumed by DSLAM nodes [8]. Therefore, remote DSLAM units (placed closer to customers) can significantly help reduce power consumption by reducing the loop lengths. Managing the larger number of remote units can be simplified by making them appear as remote line cards to the management layer. However, the efficiency of this scheme depends on the strategic placement of remote DSLAMs in the service coverage area.

This paper investigates the problem of designing and optimizing existing and green-field all-copper DSL networks by replacing large DSLAMs with strategically placed remote DSLAM units in the access network. This paper focuses on the “copper” side of the access network (see Figure 1), which is designed in a tree-based hierarchy (access node at root and customers at leaves). There can be a choice of several alternative locations to place the remote DSLAM units along this network (e.g. in Figure 1 pillar and sub-pillars). Various local parameters such as the cost of laying fiber, capex and opex of the remote DSLAM units (henceforth simply referred to as remote units), copper transmission power costs, and customer locations can affect this choice.

Fig. 1: Typical metropolitan access network structure

We investigate two scenarios. The first applies to an existing all-copper access network, where we take an all-copper tree and transforms it into a mix of copper and fiber. Each fiber connects the access node to some remote unit, which initiates multiple copper loops to the customers. Typically, the additional cost of remote units is justified by the power saving achieved through reduced copper loop lengths. We present an efficient polynomial-time algorithm to transform an all-copper tree into such a minimum-cost fiber/copper tree, using a dynamic programming solution. We assess this algorithm...
using data based on a real operator’s network. When the operator wishes to reach customers in an extended neighborhood, placing remote units using our algorithm results in significant improvements in both coverage (customers reachable from a node-site) and power consumption.

The second approach is to consider a green-field deployment, which is particularly relevant in emerging markets like India. We show that this problem is NP-hard, and present an ILP formulation. While the ILP can solve very small problem sizes (1 square kilometer in an urban area), even slightly larger problem sizes become intractable. Therefore, we also present a very fast and efficient heuristic based approach, where we first build an access tree (which determines where fiber or copper is to be laid), and then use the previous algorithm to place remote units as well as fiber and copper along this tree. For datasets that can be solved using the ILP, our heuristic approach produces results very close to optimal. For larger data sets, we show the benefit of using our algorithm on the customer coverage and power consumption.

A. Related Work

Several efforts have been made to reduce the energy consumption of DSLAM nodes by researchers [7], [8], [12], [17], [18]. The ADSL2+ standard also now defines multiple low-power modes [10]. Complimentary to these approaches, we find a cost and energy efficient access topology, given the physical parameters and costs of an access network. The placement of remote DSLAM units to create a hybrid fiber-copper network is somewhat similar to the problem of designing hybrid wireless-optical access networks. Here fiber is drawn as far as possible from the node site, and then wireless access technologies are used to connect to the end user [11], [15], [16]. Complimentary to our approach, energy-efficiency of networking infrastructure has been recently examined [5], [9], [13]. Turning off idle network elements as a dynamic network-wide optimization and rerouting traffic can further increase the energy efficiency at low traffic times [1], [3], [4].

II. REDESIGNING AN EXISTING ALL-COPPER TREE LAYOUT

The statistics, network and customer data cited in this paper are based on the wireline access network of a large Indian operator. Table I lists the terminology used in describing our algorithms. A detailed description of terminology is presented in [2]. The term “node” is used to generalize access node, customers and as well as intermediate structures i.e. pillars and sub-pillars. The term “edge” is used to denote road-segments along which fiber or copper is laid. Note that, there can be multiple intermediate levels (Figure 1 shows only 2 levels).

We now present a solution to the problem of redesigning an existing all-copper access tree into a tree with a mix of copper and fiber. We attempt to formalize the trade-off between the expenses of deploying remote units and laying additional fiber and the power saving achieved from reduced copper loops. Our algorithm identifies the locations in the network suitable for placing remote units, and the customers who will be served by them. The transformed network may have multiple copper loops as well as fibers along an edge. One fiber is needed to connect each remote unit to the access node site and one copper is needed to connect each customer to its serving DSLAM unit. We attempt to minimize the overall cost of the network. The core of the solution is a bottom-up dynamic programming based algorithm described below (pseudo code is presented in [2]).

In the original all-copper tree, any subtree with n customers needs exactly n copper loops to enter through its root. The tree-redesign algorithm traverses the tree in bottom-up manner and for each subtree t with root r, it calculates the array cost[0 to n] where n is the number of customers in t and cost[c] holds the minimum cost configuration of t if c copper loops are entering through r. If c < n, one or more remote units need to be deployed inside t and they need individual fiber lines from access node site through r. These minimum costs are calculated in following way.

A 2-D array subtree_cost[1 to K][0 to n] is calculated where r has K subtrees and t has total n customers. subtree_cost[k][c] holds the minimum cost of distributing c copper lines among first k subtree of r (subtrees can be enumerated in any order). This minimum cost is derived by considering the cost[] arrays of each of these k subtrees and the values at subtree_cost[k−1][0] to subtree_cost[k−1][c], all of which are computed already. If any subtree is a customer, a copper loop is forced to that line. The last row of subtree_cost holds the minimum cost of distributing different number of copper lines (0 to n) among all subtrees of r.

The value cost[c] for r is calculated from the value subtree_cost[K][c] by considering distributing c to n copper lines among all customers in t. The distribution is done in following way - Suppose, we are trying to distribute c′ copper lines in t. Here, c copper loops are coming from the parent of r and can originate anywhere above in the tree. As copper transmit power (power(u,v)) is a convex function of copper loop length [7], we choose c shortest customer connection from r and assign them these c copper loops, to keep the transmit power cost minimum. If c′ > c, the rest c′−c copper lines need to originate from r. In this case we include the cost of deploying required number of remote units (\(\frac{c′−c}{D}\)−rem(r)) at r and laying fiber to r (fiber(r)). For all c′ from c to n, we choose the minimum cost configuration as cost[c] at r.

This phase of algorithm ends once the value T → cost[0] is calculated. This is the minimum cost configuration for the root R (access node site) as there are no copper loops entering this node. The next phase of the algorithm traverses the tree in top-down manner and configures the entire tree to match this minimum cost configuration at root. For example, we

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Access node-site (root of T)</td>
</tr>
<tr>
<td>power(u,v)</td>
<td>Power cost for a copper line between u and v</td>
</tr>
<tr>
<td>rem(v)</td>
<td>Remote unit Deployment cost at node v</td>
</tr>
<tr>
<td>D</td>
<td>Capacity of a remote unit</td>
</tr>
<tr>
<td>fiber(v)</td>
<td>Fiber laying cost to node v from its parent</td>
</tr>
</tbody>
</table>

TABLE I: Tree redesign algorithm terminology
### Table II: Parameter values for tree reconfiguration

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum loop length</td>
<td>1500 m</td>
</tr>
<tr>
<td>Cost of laying fiber (option 1)</td>
<td>$6 per meter</td>
</tr>
<tr>
<td>Cost of remote DSLAM unit</td>
<td>$22000</td>
</tr>
<tr>
<td>Capacity (#copper ports) of remote DSLAM unit</td>
<td>50</td>
</tr>
<tr>
<td>Cost of energy</td>
<td>$0.20 per kWh</td>
</tr>
<tr>
<td>Time period to recoup capital expense</td>
<td>3 years</td>
</tr>
<tr>
<td>Number of customers</td>
<td>130</td>
</tr>
<tr>
<td>Dimensions of copper tree layout</td>
<td>1km x 1km</td>
</tr>
<tr>
<td>Type of Scenario</td>
<td>dense urban</td>
</tr>
<tr>
<td>Per user data rate</td>
<td>12 Mbps</td>
</tr>
</tbody>
</table>

Start by choosing the configuration corresponding to \( \text{cost}[0] \) at root, because this is the only possible configuration for access node site. Suppose, the root has \( K \) children and the chosen configuration distributes respectively \( c_1, c_2 \ldots c_K \) copper lines to these nodes. We then select the configuration of \( \text{cost}[c_1] \) at first child, configuration of \( \text{cost}[c_2] \) at second child and likewise \( \text{cost}[c_K] \) at the \( R^{th} \) child. After this, we continue to set the configurations of nodes further below the tree until all nodes are visited. The correctness and the polynomial complexity of this algorithm is described in [2].

### A. Experiments

We conducted our experiments on the network layout of a real urban all-copper access tree in a large Indian city and realistic cost values (see Table II) collected from the operator. We get digging costs of fiber and copper from the field-engineers directly. Figure 2 shows a typical relation between line driver power and loop length for a set of connections with fixed data rate of 12Mbps and an SNR gap of 25db (with crosstalk in standard urban setting). As the plot suggests, above a loop length of 1500m, sustaining 12Mbps with 25db SNR gap level is not possible. Therefore, for lines longer than this limit, remote DSLAM units are necessary to shorten the copper loop lengths. We translate all recurring expenses into single upfront costs over a fixed period of time. Detailed explanations of all costs and cost-models used here, is presented in [2].

![Fig. 2: Line driver power (25 db SNR gap) vs loop length assumed in a typical urban bundling scenario.](image1)

Next, we vary the number of customers in the network from 150 to 900 and execute our algorithm on it. Though majority of customers are within the reach of copper loops, we still achieve around power saving of 100 milliwatts per line. Detailed plots of these experiments are given in [2].

Note that the power savings from the use of remote DSLAM units alone cannot fully justify their additional capital expenses. However, remote units can also enable high bit-rate DSL services for a much larger set of customers than what is feasible with pure copper access trees from a single node-site. We want to quantify this benefit as part of the optimization, in our future works.

### III. Designing a Green-field Access Network

In the green-field version, we are given a graph \( G = (V, E) \) where the edges represent road sections along which a trench can be dug, there is a designated node representing the central office, and the remaining nodes represent either road intersections or customers. There are costs along each edge giving the copper transmission power on that edge, the cost to dig a trench along that stretch of road, and the costs to lay copper / fiber within such a trench. Some nodes are designated as potential locations for a remote DSLAM and these nodes have associated cost to install a remote DSLAM at that node. All DSLAMs have a capacity limit. Our goal is to determine a subset of the nodes at which to place remote units (and associate a set of customers) and a tree of edges along which trenches will be dug to allow for fiber from the central office to each remote DSLAM and for copper from remote units to each associated customer.

![Fig. 3: Effect of scaling network edge lengths on the costs and power consumption of the optimal access tree.](image2)  

(a)  

(b)

It is easy to show that this design problem is NP-complete [2] and so we develop an integer linear program (ILP) and a heuristic approach. We use the optimal results produced by the ILP to measure the quality of the heuristic solutions for smaller, more tractable datasets.
A. Integer Linear Program

The parameters and variables of the ILP are shown in Table III. The ILP’s objective is to minimize:

\[
\sum_{e_{xy} \in E} T_{xy} \cdot \text{Dig}(e_{xy}) + \sum_{i \in R} d_i \cdot C_D + \sum_{e_{xy} \in E} n_{xy}^a \cdot f_i^C(e_{xy})
\]

\[
+ \sum_{i \in U} \sum_{e_{xy} \in E} c_{xy}[i] \cdot \{ f_i^I(x, y) + f_i^I(e_{xy}) \}
\]

I is diging + DSLAM installation cost, II is fiber installation cost and III is copper transmit power + installation cost. subject to the following constraints:

\[
\sum_{y \in N(x)} c_{xy}[i] - \sum_{y \in N(x)} c_{yx}[i] = 0 \quad \forall x \in R_N, \forall i \in U
\]

\[
\sum_{y \in N(x)} n_{xy}^a - \sum_{y \in N(x)} n_{yx}^a = 0 \quad \forall x \in R_N
\]

\[
\sum_{j \in N(i)} n_{ji}^a - \sum_{j \in N(i)} n_{ij}^a = d_i \quad \forall i \in R
\]

\[
\sum_{k \in U} \left( \sum_{j \in N(i)} c_{kj}[k] - \sum_{j \in N(i)} c_{jk}[k] \right) \leq d_i \cdot D \quad \forall i \in R
\]

\[
\sum_{i \in U, y \in N(S)} c_{xy}[i] = \sum_{i \in U, y \in N(S)} c_{yx}[i] = \sum_{y \in N(S)} n_{xy}^a = 0
\]

\[
\sum_{y \in N(S)} n_{xy}^a = \sum_{i \in U} d_i
\]

\[
\sum_{y \in N(i)} c_{yi}[i] = 1, \quad \sum_{y \in N(i)} c_{yi}[i] = 0 \quad \forall i \in U
\]

\[
\sum_{y \in N(i)} c_{yi}[j] - \sum_{y \in N(i)} c_{yi}[j] = 0 \quad \forall i, j \in U, j \neq i
\]

\[
\sum_{y \in N(i)} n_{yi}^a - \sum_{y \in N(i)} n_{yy}^a = 0 \quad \forall i, j \in U, j \neq i
\]

\[
\forall e_{xy} \in E, i \in U:
\]

\[
c_{xy}[i] + c_{yx}[i] + n_{xy}^a + n_{yx}^a \leq T_{xy} \cdot (|R| + |U|)
\]

\[
\sum_{e_{xy} \in E} c_{xy}[i] \cdot L_{xy} \leq L
\]

Detailed explanation of this ILP can be found in [2]. Note that we have assumed the transmission power \( f_i^T(x, y) \) over copper to be linear and additive. Though in reality, the actual power consumed will be less than the power obtained by adding up power over the individual segments, this simplification is required for a valid ILP formulation.

B. Heuristic Approach

The ILP turns out to be intractable over any reasonably large inputs, and therefore we now present a simple and fast heuristic to solve the greenfield problem. Typically the cost to dig a trench will be a major factor in the overall cost of design. The higher the trenching cost, the closer the overall problem resembles the minimum-cost Steiner tree problem. Therefore a reasonable heuristic approach would be to first find a low cost (in terms of the trenching cost) tree \( T \), that is, a Steiner tree that connects all the customers to the central office, then apply the dynamic programming algorithm described in Section II to obtain the complete design. In the dynamic programming step, we assign a zero cost to the trenching, since that is accounted for in the Steiner tree cost. Instead, the dynamic program balances the cost of the remote units against the cost of power saving.

Multiple Steiner tree approximation algorithms exist. We use a simple algorithm with a 2-approximation ratio described in [6] and refer to it as the “Steiner” method. We also use an alternative method of building an MST and then deleting subtrees that do not contain any customers and denote this approach as “MST” method. Note that, a better and more complex Steiner tree algorithm such as by Robins and Zelikovsky [14] with 1.55 approximation factor can also be used.

C. Experiments

We assessed the ILP and heuristic approaches on a dataset generated for two Indian cities—Bhopal and Kolkata. We extracted a square area from the street map of each city, and used the street segments as edges and their end points as candidate locations for placing remote DSLAMs. The customer locations were chosen at random from the segment ends. Table IV lists the various datasets and their details along with the feasible coverage without any remote DSLAM unit.

Figure 4a shows the relative performance of our two heuristic-based approaches: Steiner and MST. Both are very close, and we can simply run both and select the better solution for every dataset. Figure 4b shows the performance of the heuristic approaches compared with the ILP for smaller datasets (tractable for the ILP). The heuristic’s performance is very close (within 1.5%) to the optimal ILP solution. Figure 5 shows how our heuristic approaches reduce per-user power consumption for different data-sets. Note that, the heuristic approaches also always achieve 100% coverage (compare with the last column in Table IV) in addition to this power saving.
<table>
<thead>
<tr>
<th>City Name</th>
<th>Data Set Name</th>
<th>Dimension (km)</th>
<th>No. of Nodes</th>
<th>No. of Edges</th>
<th>No. of Customers</th>
<th>coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kolkata</td>
<td>K4.0</td>
<td>1.5</td>
<td>20</td>
<td>38</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>K3.0</td>
<td>4.0</td>
<td>177</td>
<td>2692</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>K2.0</td>
<td>2.0</td>
<td>383</td>
<td>1286</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>K1.0</td>
<td>1.0</td>
<td>91</td>
<td>188</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>K0.5</td>
<td>0.5</td>
<td>20</td>
<td>38</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>K0.8</td>
<td>0.8</td>
<td>46</td>
<td>92</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>K1.0</td>
<td>1.0</td>
<td>92</td>
<td>184</td>
<td>50</td>
<td>90</td>
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<tr>
<td></td>
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<td>2.0</td>
<td>967</td>
<td>1982</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td></td>
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<td>3.0</td>
<td>1522</td>
<td>3398</td>
<td>600</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>K4.0</td>
<td>4.0</td>
<td>2317</td>
<td>5190</td>
<td>800</td>
<td>10</td>
</tr>
</tbody>
</table>

TABLE IV: Details of graphs used in our experiments.

IV. CONCLUSIONS

Reducing the power consumption of DSL equipment has become an important research problem. Complimentary to most approaches that focused on careful power management solutions to reduce the line driver power for individual lines without affecting line stability, our solution looks instead at how to redesign DSL access networks at an architectural level. As far as we know, this is the first attempt to look at the problem from an access network-wide view. By efficiently placing remote DSLAM units between the access node site and the individual customers, we attempt to balance the cost of these units and laying fiber to them with the savings in energy consumption and increased customer reach. In the greenfield network layout problem, our heuristic technique produces results that are very close to optimal approach. Our approach can be used by operators to redesign their existing networks, or to design green-field deployments in a power-efficient manner.

REFERENCES