Planning Multitechnology Access Networks with Performance Constraints

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Abstract. Considering the number of access network technologies and the investment needed for the "last mile" of a solution, in today's highly competitive markets, planning tools are crucial for the service providers to optimize the network costs and accelerate the planning process. In this paper, we propose to tackle the problem of planning access networks composed of four technologies/architectures: the digital subscriber line (xDSL) technologies deployed directly from the central office (CO), the fiber-to-the-node (FTTN), the fiber-to-the-micro-node (FTTn) and the fiber-to-the-premises (FTTP). A mathematical programming model is proposed for this planning problem that is solved using a commercial implementation of the branch-and-bound algorithm. Next, a detailed access network planning example is presented followed by a systematic set of experiments designed to assess the performance of the proposed approach.

Keywords: Access network planning, digital subscriber line (xDSL) technologies, xDSL from the central office, fiber-to-the-node (FTTN), fiber-to-the-micro-node (FTTn), fiber-to-the-premises (FTTP), integer mathematical programming, branch-and-bound algorithm.

1 Introduction

Due to the increasing demand for Internet protocol (IP) based services, the digital subscriber line (DSL) service providers are investing incessantly in their access network infrastructure. For instance, with the introduction of the high definition television (HDTV) over IP (IPTV), new access network architectures and technologies are currently considered to improve the access rate, principally in the downstream direction. Typically, a minimum of 25 Mbps downstream is required per customer for a "triple play" service, i.e., to offer two HDTV signals, two standard definition TV (SDTV) signals, the telephony over IP (ToIP) service and a high speed Internet (HSI) access.

It is clear that the best technical solution is to deploy a fiber-to-the-premises (FTTP) network using, for instance, a passive optical network (PON) as illustrated in Figure 1 (b). The gigabit-capable PON (GPON) technology standardized by the ITU-T G.984.x [7] and the Ethernet PON (EPON) standardized by the IEEE 802.3ah [4] are currently available. However, those fiber-based access

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technologies are still costly and taking into account time-to-market pressures and short-term economic concerns, those technologies cannot be widely deployed today for the majority of the DSL service providers.

The "classical" way of deploying xDSL, e.g., the asymmetric DSL (ADSL, ADSL2 and ADLS2+) (see ITU-T G.992.x [6]) and the very-high-speed DSL (VDSL and VDSL2) (see ITU-T G.993.x [8]), is to install the DSL access multiplexers (DSLAMs) in the COs. With the existing copper infrastructure, the majority of the plain old telephone service (POTS) customers are not qualified for a "triple play" service considering the length of the copper loops and their characteristics such as the number of bridge taps, the number of disturbers per binder, etc. Typically, the maximum loop length for a 25 Mbps service is about 900 meters with VDSL2, one bridge tap and three disturbers per 25-pair binder. As a result, new architectures and technologies have been proposed to improve the performance of the xDSL technologies. The first one, the fiber-to-the-node (FTTN), allows to reduce the copper loop lengths by installing small DSLAMs (i.e., the nodes) at the outside plant interface (OPI) cabinet locations instead of installing them in the COs, as illustrated in Figure 1 (c). Typically, the nodes are supporting both DSL-based FTTN and Ethernet-based FTTN. However, Ethernet-based FTTN is rarely considered as an option for FTTP since important power distribution, batteries, etc. are needed in the outside plant. The second architecture, the fiber-to-the-micro-node (FTTn), allows to install micro-nodes, i.e., small sealed expansion modules, in the outside plant in order to connect the customers far from the cabinets with a good performance (see Figure 1 (c)). An interesting technology is the cable bonding (see ITU-T G.998.1 [9] and G.998.2 [10]). This technology allows the service providers of using two or more copper loops per customer in order to improve the performance of the xDSL technologies for a given loop length and/or to have longer loops for a given performance. Considering that most of POTS customers have two copper loops, this technology is very interesting. Finally, the dynamic spectrum management (DSM) (also called far end crosstalk (FEXT) cancellation), is a promising technology to increase the performance of VDSL2. This technology increases the access rate by adapting the transmit spectra considering the actual time-variable FEXT interference. However, this technology is not standardized yet (see ITU-T temporary document SD-064 [11]).

A viable FTTP deployment scenario consists of using FTTP in the greenfield and to introduce it gradually in the brownfield while considering FTTN. FTTN is then an incremental step to FTTP. Planning a such access network is complex and, in today's highly competitive markets, planning tools are crucial for the service providers to optimize the network costs and accelerate the planning process.

In this paper, we propose to tackle the problem of planning multitechnology access networks considering single-family units (SFUs) and small/medium multi-dwelling units (MDUs) for one or many digital serving areas (DSAs). (For large MDUs and business services, the fiber-to-the-building (FTTB) (point-to-point) architecture can be used, see Figure 1 (a).)

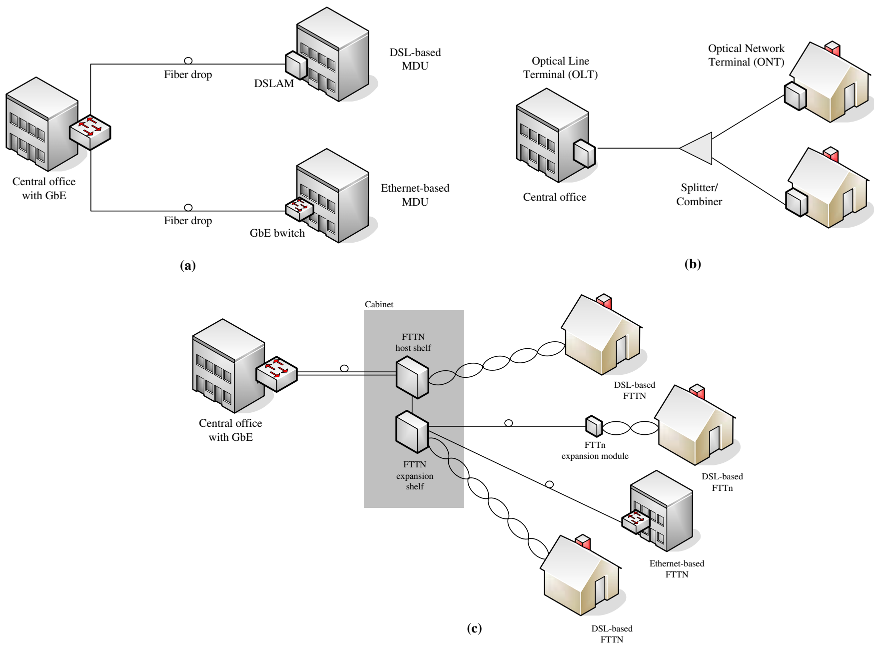

Fig. 1. Access network architectures/technologies: a) Fiber-to-the-building (FTTB) (point-to-point) network; b) Basic passive optical network (PON); c) Fiber-to-the-node (FTTN) network

The planning problem deals with:

– connecting each POTS customer requiring IP services (e.g., IPTV, ToIP, HSI, etc.) with a requested class of service to the network with xDSL technologies (ADSL, ADSL2, ADSL2+ and VDSL2) (with or without bonding) or with GPON;
– connecting each new non-POTS customer to the network with GPON;
– updating, if necessary, the connection of each DSL customer requiring a better class of service;
– locating new DSLAMs in the COs, nodes at the cabinet locations and micro-nodes in the field (at potential sites in the brownfield preselected by the network planner);
– selecting the types of the new DSLAMs, nodes and micro-nodes;
– selecting the number and the types of new line cards to insert in the DSLAMs and in the nodes;
– connecting the new nodes and micro-nodes to the COs with optical links;
– installing, if necessary, new cabinets in the greenfield to install the splitters;
– locating new optical splitters and connecting them while respecting the PON topology selected by the network planner.

The objective is to minimize the total cost for updating the access network.

In the literature, several papers have been published on access network design problems (for "classical" access network design problems, see [1,2] and the references contained therein). The most related papers are by Haidine *et al.* [3] and Zhao *et al.* [17] on the design problem of VDSL access network with reliability and performance constraints. Integer mathematical programming models are proposed as well as heuristic algorithms based on simulated annealing, tabu search and genetic algorithms. Other papers are concentrated on the FTTP network design problem, for instance, see [14,15,16]. In these papers, the authors propose genetic algorithms for the design of passive optical networks with realistic assumptions.

None of the above mentioned references considered the multitechnology access network planning (or design, expansion, update, etc.) problem presented. Moreover, the performance of the xDSL technologies combined with the location of the DSLAMs, nodes and micro-nodes and the possibility of cable bonding has never been considered.

This paper is organized as follows. In Section 2 we present the mathematical notation, the cost functions, a preprocessing algorithm and the integer mathematical programming model for the multitechnology access network planning problem. In Section 3, we present a detailed access network planning example followed by a systematic set of experiments designed to assess the performance of the proposed approach. Conclusions and further works are presented in Section 4.

2 The Modeling Framework

2.1 The Notation

The following notation is used throughout this paper.

Sets

- C, the set of classes of service;
- D, the set of xDSL technologies used in the access network such that $D = \{1, 2, 3, 4\}$ where $d = 1$ for ADSL, $d = 2$ for ADSL2, $d = 3$ for ADSL2+ and $d = 4$ for VDSL2;
- $N = N_J \cup N_O \cup N_P \cup N_M$, the set of positions in the network;
  - $N_J = N_{J1} \cup N_{J2}$, the set of cabinet locations where N_{J1} is the set of OPI cabinets in the brownfield and N_{J2} the set of potential sites to install new cabinets in the greenfield;
    - ξ_j, the maximum number of nodes that can be installed at cabinet location $j \in N_{J1}$;
    - π_j, the maximum number of splitters that can be installed at cabinet location $j \in N_J$;
    - θ_j, the maximum length of a fiber from cabinet location $j \in N_J$ to a point of demand;
    - μ, the maximum number of customers that can be served with a GPON tree to offer the better class of service;

- N_O, the set of COs;
  - κ_o, the maximum number of DSLAMs that can be installed in CO $o \in N_O$;
  - $o(j)$, the associated CO for the cabinet location $j \in N_{J1}$;
- $N_P = N_{P1} \cup N_{P2}$, the set of points of demand where N_{P1} is the set of POTS points of demand (i.e., connected with copper loops) and N_{P2} the set of non-POTS points of demand;
  - α_p^c, the number of customers of class $c \in C$ at the point of demand $p \in N_P$;
  - $\alpha_p = \sum_{c \in C} \alpha_p^c$, the total number of customers at the point of demand $p \in N_P$;
  - β_p^c, a 0-1 constant such that $\beta_p^c = 1$ if and only if $\alpha_p^c > 0$;
  - $o(p)$, the associated CO for the point of demand $p \in N_{P1}$;
  - $j(p)$, the associated cabinet for the point of demand $p \in N_{P1}$;
  - $\gamma_{o(p),p}$, the length of the loops from the CO $o(p) \in N_O$ to the point of demand $p \in N_{P1}$;
  - $\gamma_{j(p),p}$, the length of the loops from the cabinet $j(p) \in N_{J1}$ to the point of demand $p \in N_{P1}$;
  - $\lambda_{o(p),p}$, the number of customers at the point of demand $p \in N_{P1}$ connected to a DSLAM installed in CO $o(p) \in N_O$ necessitating bonding;
  - $\lambda_{j(p),p}$, the number of customers at the point of demand $p \in N_{P1}$ connected to a node installed at the cabinet location $j(p) \in N_{J1}$ necessitating bonding;
  - $\eta_p^{c,d,b}$, the maximum length for the loops (in km) to offer a service of class $c \in C$ to the point of demand $p \in N_{P1}$ with the xDSL technology $d \in D$ and with b bonded loops ($b \in \{1, 2\}$);
  - $\rho_{j,p}$, the length of the fiber to install from the cabinet $j \in N_J$ to the point of demand $p \in N_P$;
- N_M, the set of sites to installed the micro-nodes;
  - N_M^p, the set of micro-node sites that can be used for the point of demand $p \in N_{P1}$;
  - $\gamma_{m,p}$, the length of the loops from the site $m \in N_M^p$ to the point of demand $p \in N_{P1}$;
  - $\lambda_{m,p}$, the number of customers at the point of demand $p \in N_{P1}$ connected to a micro-node installed at the site $m \in N_M$ necessitating bonding;

– $T = T_D \cup T_N \cup T_M$, the set of DSLAMs, nodes and micro-nodes types where T_D is the set of DSLAMs types, T_N the set of nodes types and T_M the set of micro-node types;
  - χ^t, the number of slots for a DSLAM of type $t \in T_D$;
  - ν^t, the number of slots for a node of type $t \in T_N$;
  - δ^t, the maximum number of customers that can be connected to a micro-node of type $t \in T_M$;

– L, the set of maximum capacity line cards that can be inserted in the DSLAM and node types;

– $\phi^{\ell(t)}$, the maximum number of customers (without bonding) that can be connected to a line card for a node of type $t \in T_D \cup T_N$.

Variables

– u_o^t, the number of DSLAMs of type $t \in T_D$ installed in CO $o \in N_O$;
– u_j^t, the number of nodes of type $t \in T_N$ installed at cabinet location $j \in N_{J1}$;
– u_m^t, a 0-1 variable such that $u_m^t = 1$ if and only if a micro-nodes of type $t \in T_M$ is installed at site $m \in N_M$;
– v_o^ℓ, the number of line cards of type $\ell \in L$ in the DSLAMs installed in the CO $o \in N_O$;
– v_j^ℓ, the number of line cards of type $\ell \in L$ in the nodes installed at the cabinet location $j \in N_{J1}$;
– w_j, a 0-1 variable such that $w_j = 1$ if and only if a cabinet is installed at site $j \in N_J$;
– $x_{o(p),p}$, a 0-1 variable such that $x_{o(p),p} = 1$ if and only if the point of demand $p \in N_{P1}$ is connected to a DSLAM installed in the CO $o(p) \in N_O$;
– $x_{j(p),p}$, a 0-1 variable such that $x_{j(p),p} = 1$ if and only if the point of demand $p \in N_{P1}$ is connected to a node installed at the cabinet location $j(p) \in N_{J1}$;
– $x_{m,p}$, a 0-1 variable such that $x_{m,p} = 1$ if and only if the point of demand $p \in N_{P1}$ is connected to a micro-node installed at the site $m \in N_M^p$;
– $y_{j,p}$, a 0-1 variable such that $y_{j,p} = 1$ if and only if the point of demand $p \in N_P$ is connected with a fiber to a splitter installed at the cabinet location $j \in N_J$;
– $y_{o(j),j}$, the number of splitters installed at the cabinet location $j \in N_J$ as well as the number of fibers between this cabinet and the CO $o(j) \in N_O$.

In our model, the existing access network is identified by the decision variables overlined. For instance, if the point of demand $p \in N_P$ is connected directly to a DSLAM located in the CO $o \in N_O$ in the existing network, then $\overline{x}_{p,o} = 1$. Similarly, if one DSLAM of type $t \in T_D$ is installed in the CO $o \in N_O$ in the existing network, then $\overline{u}_o^t = 1$.

Cost Parameters

– $a_{o(p),p}$, the minimum cost (in \$) of connecting the point of demand $p \in N_{P1}$ to a DSLAM installed in the CO $o(p) \in N_O$ while respecting the class of service for each customer;
– $A_{o(p),p}$, the cost (in \$) of disconnecting the point of demand $p \in N_{P1}$ from the DSLAM installed in the CO $o(p) \in N_O$;
– $a_{j(p),p}$, the minimum cost (in \$) of connecting the point of demand $p \in N_{P1}$ to a node installed at the cabinet location $j(p) \in N_{J1}$ while respecting the class of service for each customer;
– $A_{j(p),p}$, the cost (in \$) of disconnecting the point of demand $p \in N_{P1}$ from the node installed at the cabinet location $j(p) \in N_{J1}$;
– $a_{m,p}$, the minimum cost (in \$) of connecting the point of demand $p \in N_{P1}$ to a micro-node installed at the site $m \in N_M^p$ while respecting the class of service for each customer;

- $A_{m,p}$, the cost (in \$) of disconnecting the point of demand $p \in N_{P1}$ to a micro-node installed at the site $m \in N_M^p$;
- b_o^t, the cost (in \$) of a DSLAM of type $t \in T_D$ and installing it in CO $o \in N_O$;
- B_o^t, the cost (in \$) of removing a DSLAM of type $t \in T_D$ installed in CO $o \in N_O$;
- b_j^t, the cost (in \$) of a node of type $t \in T_N$ and installing it at cabinet location $j \in N_{J1}$;
- B_j^t, the cost (in \$) of removing a node of type $t \in T_N$ installed at cabinet location $j \in N_{J1}$;
- b_m^t, the cost (in \$) of a micro-node of type $t \in T_M$ and installing it at site $m \in N_M$;
- B_m^t, the cost (in \$) of removing a micro-node of type $t \in T_M$ installed at site $m \in N_M$;
- c^ℓ, the cost (in \$) of a line card of type $\ell \in L$ and installing it;
- C^ℓ, the cost (in \$) of removing a line card of type $\ell \in L$;
- $d_{o(j),j}$, the cost (in \$) of a splitter and installing it at the cabinet location $j \in N_J$ and connecting it to the CO $o(j) \in N_O$;
- $e_{j,p}$, the cost (in \$) of connecting with a fiber the point of demand $p \in N_P$ to a splitter installed at the cabinet location $j \in N_J$;
- f_j, the cost (in \$) of a new cabinet and installing it at site $j \in N_{J2}$;
- g_p, the cost (in \$) of not connecting the customers located at point of demand $p \in N_P$.

2.2 Cost Functions

The total cost function is composed of the cost of the xDSL from the CO network, the cost of the FTTN network, the cost of the FTTn network and the cost of the FTTP network.

The cost of the xDSL from the CO network, denoted Z_{DSL-CO}, given by the following equation, includes the cost of connecting and disconnecting the points of demand, the cost of installing and removing the DSLAMs and the cost of installing and removing line cards.

$$\begin{aligned}
&\sum_{p \in N_{P1}} \left(a_{o(p),p} \left(x_{o(p),p} - \overline{x}_{o(p),p} \right)^+ + A_{o(p),p} \left(\overline{x}_{o(p),p} - x_{o(p),p} \right)^+ \right) \\
&+ \sum_{o \in N_O} \sum_{t \in T_D} \left(b_o^t \left(u_o^t - \overline{u}_o^t \right)^+ + B_o^t \left(\overline{u}_o^t - u_o^t \right)^+ \right) \\
&+ \sum_{o \in N_O} \sum_{t \in T_D} \left(c_o^{\ell(t)} \left(v_o^{\ell(t)} - \overline{v}_o^{\ell(t)} \right)^+ + C_o^{\ell(t)} \left(\overline{v}_o^{\ell(t)} - v_o^{\ell(t)} \right)^+ \right) . \qquad (1)
\end{aligned}$$

The cost of the FTTN network, denoted Z_{FTTN}, given by the following equation, includes the cost of connecting and disconnecting the points of demand, the cost of installing and removing the nodes and the cost of installing and removing line cards.

$$\sum_{p\in N_{P1}} \left(a_{j(p),p} \left(x_{j(p),p} - \overline{x}_{j(p),p} \right)^+ + A_{j(p),p} \left(\overline{x}_{j(p),p} - x_{j(p),p} \right)^+ \right)$$
$$+ \sum_{j\in N_{J1}} \sum_{t\in T_N} \left(b_j^t \left(u_j^t - \overline{u}_j^t \right)^+ + B_j^t \left(\overline{u}_j^t - u_j^t \right)^+ \right)$$
$$+ \sum_{j\in N_{J1}} \sum_{t\in T_N} \left(c_j^{\ell(t)} \left(v_j^{\ell(t)} - \overline{v}_j^{\ell(t)} \right)^+ + C_j^{\ell(t)} \left(\overline{v}_j^{\ell(t)} - v_j^{\ell(t)} \right)^+ \right). \quad (2)$$

The cost of the FTTn network, denoted Z_{FTTn}, given by the following equation, includes the cost of connecting and disconnecting the points of demand and the cost of installing and removing the micro-nodes.

$$\sum_{p\in N_{P1}} \sum_{m\in N_M} \left(a_{m,p} \left(x_{m,p} - \overline{x}_{m,p} \right)^+ + A_{m,p} \left(\overline{x}_{m,p} - x_{m,p} \right)^+ \right)$$
$$+ \sum_{m\in N_M} \sum_{t\in T_M} \left(b_m^t \left(u_m^t - \overline{u}_m^t \right)^+ + B_m^t \left(\overline{u}_m^t - u_m^t \right)^+ \right). \quad (3)$$

The cost of the FTTP network, denoted Z_{FTTP}, given by the following equation, includes the cost of connecting the points of demand, the cost of the splitters and fibers, and the cost of the new cabinets.

$$\sum_{j\in N_J} \left(\sum_{p\in N_P} e_{j,p} \left(y_{j,p} - \overline{y}_{j,p} \right)^+ + d_{o(j),j} \left(y_{o(j),j} - \overline{y}_{o(j),j} \right)^+ \right) + \sum_{j\in N_{J2}} f_j w_j. \quad (4)$$

2.3 Preprocessing

Several variables can be fixed to zero and the number of constraints reduced before solving the model presented in the next subsection. We propose the preprocessing algorithm presented below.

Preprocessing

Step 1: (Initialization)

- **1.1** For all $p \in N_{P1}$, set $\lambda_{o(p),p} = 0$ and $\lambda_{j(p),p} = 0$.
- **1.2** For all $p \in N_{P1}$ and $m \in N_M^p$, set $\lambda_{m,p} = 0$.

Step 2: (Fixing $x_{o(p),p}$ variables)

- **2.1** For all $p \in N_{P1}$ and $c \in C$ do
  If $\beta_p^c = 1$, $\gamma_{o(p),p} > \eta_p^{c,4,1}$ and $\gamma_{o(p),p} \le \eta_p^{c,4,2}$, set $\lambda_{o(p),p} := \lambda_{o(p),p} + \alpha_p^c$.
- **2.2** For all $p \in N_{P1}$ and $c \in C$ do
  If $\beta_p^c = 1$, $\gamma_{o(p),p} > \eta_p^{c,4,2}$, set $x_{o(p),p} := 0$.

Step 3: (Fixing $x_{j(p),p}$ variables)

- **3.1** For all $p \in N_{P1}$ and $c \in C$ do
  If $\beta_p^c = 1$, $\gamma_{j(p),p} > \eta_p^{c,4,1}$ and $\gamma_{j(p),p} \le \eta_p^{c,4,2}$, set $\lambda_{j(p),p} := \lambda_{j(p),p} + \alpha_p^c$.
- **3.2** For all $p \in N_{P1}$ and $c \in C$ do
  If $\beta_p^c = 1$, $\gamma_{j(p),p} > \eta_p^{c,4,2}$, set $x_{j(p),p} := 0$.

Step 4: (Fixing $x_{m,p}$ variables)

4.1 For all $p \in N_{P1}$, $m \in N_M^p$ and $c \in C$ do
If $\beta_p^c = 1$, $\gamma_{m,p} > \eta_p^{c,4,1}$ and $\gamma_{m,p} \leq \eta_p^{c,4,2}$, set $\lambda_{m,p} := \lambda_{m,p} + \alpha_p^c$.

4.2 For all $p \in N_{P1}$, $m \in N_M^p$ and $c \in C$ do
If $\beta_p^c = 1$, $\gamma_{m,p} > \eta_p^{c,4,2}$, set $x_{m,p} := 0$.

Step 5: (Fixing $y_{j,p}$ variables)

5.1 For all $p \in N_P$ and $j \in N_J$ do
If $\rho_{j,p} > \theta_j$, set $y_{j,p} := 0$.

2.4 The Model

The model for the multitechnology access network planning problem, denoted P, is presented in Appendix A.

3 Numerical Results

The algorithm was programmed in the C language on a Sun Java workstation under Linux with an AMD Opteron 150 CPU and 2 GB of RAM.

Three classes of service are considered for the tests (5, 15 and 25 Mbps) as well as two xDSL technologies (ADSL2+ and VDSL2). The characteristics of the DSLAMs, nodes and micro-nodes are presented respectively in tables 1, 2 and 3 (note that the costs presented include the installation costs). The maximal loop length per xDSL technology and class of service is presented in Table 4. Moreover, the cost for connecting a node, a micro-node or a splitter to a CO is \$1000 plus \$2000 per kilometer of fiber. The cost for connecting a customer to a DSLAM or a node is \$100 without bonding and \$200 with bonding, the cost for connecting a customer to a micro-node is \$200 without bonding and \$300 with bonding. Finally, the cost of a 1×32 splitter is \$1200 and the cost of connecting it to a customer is \$500 plus \$2000 per kilometer of fiber.

For the tests, the optimal solutions are obtained by using the CPLEX Mixed Integer Optimizer 9.0 (for more information about CPLEX [5]). The algorithm used by CPLEX is the branch-and-bound algorithm. The default settings of CPLEX are used and the branch-and-bound tree memory limit was set to 500 MB and the CPU time limit to 24 hours.

Table 1. Characteristics of the DSLAMs

Maximum number per CO	4
Number of slots	9
Number of ports per card	48
Cost per node [\$]	16000
Removing cost per DSLAM [\$]	200
Cost per card [\$]	3200
Removing cost per card [\$]	50

Table 2. Characteristics of the nodes

Maximum number per cabinet	2
Number of slots	4
Number of ports per card	48
Cost per node [$]	9000
Removing cost per node [$]	200
Cost per card [$]	3200
Removing cost per card [$]	50

Table 3. Characteristics of the micro-nodes

Number ports	48
Cost per micro-node [$]	5000
Removing cost per micro-node [$]	200

Table 4. Maximum loop length per xDSL technology and class of service (with one bridge tap and 3 disturbers per 25-pair binder)

ADSL2+		
Class of service	Maximal distance	
	Without bonding [m]	With bonding [m]
5 Mbps	1500	3000
15 Mbps	800	1600
25 Mbps (IPTV)	N/A	1000
VDSL2		
Class of service	Maximal distance	
	Without bonding [m]	With bonding [m]
5 Mbps	2000	4000
15 Mbps	1200	2400
25 Mbps (IPTV)	900	1800

3.1 An Illustrative Example

The example illustrated in Figure 2 has two cabinets (DSAs) and 10 potential sites per DSA to install the micro-nodes. The number of points of demand is 590 (each point of demand represents up to 30 customers). These DSAs are on the Bell Canada's service territory located at the Nuns' Island (officially Ile-des-Sœurs).

In the existing network, the number of POTS customers with a HSI access service is 1098 (358 (5 Mbps); 449 (15 Mbps); 291 (25 Mbps)), the number of non-POTS customers with a HSI access service is 141 (all in the greenfield of DSA #1), the number of nodes is two per cabinet (with seven line cards inserted in the nodes at each cabinet location), the number of splitters installed is 10 at each cabinet location and one micro-node is installed at micro-node site #7 of the DSA #2.

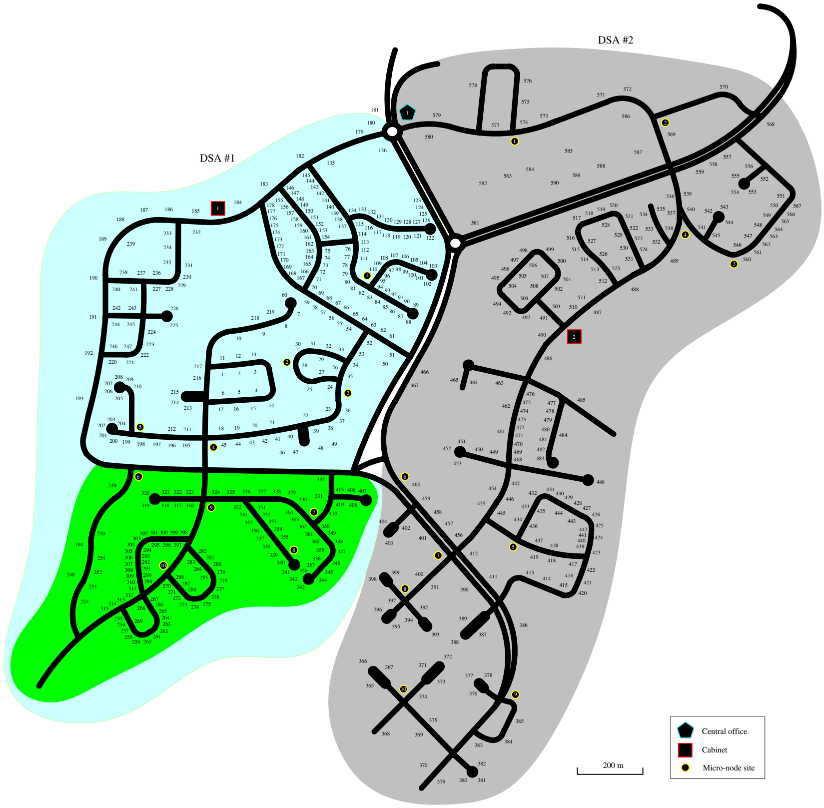

Fig. 2. The location of the points of demand, cabinets and potential micro-node sites for the example

The number of new POTS customers is 956 (345 (5 Mbps); 373 (15 Mbps); 238 (25 Mbps)) and the number of new non-POTS customers is 134. The cost of the solution found by CPLEX is $359 922 and it took 5.0 seconds of CPU time to find it. In the updated network, a new DSLAM with eight line cards is installed in the CO, two additional line cards are inserted in the nodes (one per cabinet location), eight additional splitters are installed in cabinet #1 and seven in cabinet #2 and, finally, a new micro-node is installed at micro-node site #5 of the DSA #2.

An additional network expansion is considered to obtain the final network with 1085 new POTS customers (333 (5 Mbps); 352 (15 Mbps); 400 (25 Mbps)) and 105 new non-POTS customers. The cost of the solution found by the algorithm is $407 664 and it took 9.7 seconds of CPU time to find it. In the updated network, a new DSLAM with nine line cards is installed in the CO, six additional splitters are installed in cabinet #1 and 14 in cabinet #2 and, finally, two new micro-nodes are installed, one at site #2 of the DSA #1 and one at site #7 of the DSA #2.

If all customers requesting the 25 Mbps class of service, in the optimal final network, no DSLAM is installed in the CO. The number of nodes is two per cabinet, the maximum allowed, the number of micro-nodes installed is 13 and the number of splitters is 66. In fact, for this example, when the demand for the 25 Mbps class of service is increasing, the DSL from the CO architecture architecture is less used.

3.2 Performance Evaluation

In this subsection, we use a systematic set of experiments to assess the performance of the proposed approach. Each test problem was generated as follows. First, a starting network is designed and for each starting network, an evolution problem is created by generating the location of the new points of demand in the square of side length 10 km following a uniform distribution. The number of customers at each new point of demand is randomly selected in the interval [1,5] and the class of service of each customer is also selected randomly.

Table 5. Numerical results for $|N_O| = 5$, $|N_{J1}| = 5$, $|N_{J2}| = 5$, $|N_M| = 10|N_{J1}|$ and 150 (100 POTS and 50 non-POTS) points of demand (PoD) already connected

New POTS PoD	New non-POTS PoD	OPT	
		Value [$]	CPU [sec]
100	50	449 000	1.6
100	100	728 236	0.9
100	150	979 678	5.2
100	200	1 224 950	1.8
200	50	629 044	15.1
200	100	748 922	4.4
200	150	1 076 420	4.6
200	200	1 566 314	246.2
300	50	669 892	6560.2
300	100	989 478	71.9
300	150	1 234 862	10.4
300	200	1 577 882	3389.1
400	50	834 846	83.1
400	100	ML(1 101 174)	7771.0
400	150	1 520 588	243.8
400	200	1 688 232	36.4
500	50	942 792	4365.1
500	100	ML(1 248 092)	8951.2
500	150	ML(1 412 823)	8443.5
500	200	2 037042	264.4

Table 6. Numerical results for $|N_O| = 5$, $|N_{J1}| = 10$, $|N_{J2}| = 5$, $|N_M| = 20|N_{J1}|$ and 150 (100 POTS and 50 non-POTS) points of demand (PoD) already connected

New POTS PoD	New non-POTS PoD	OPT	
		Value [$]	CPU [sec]
100	50	371 682	4.5
100	100	650 334	7.5
100	150	911 794	2.6
100	200	1 126 212	4.2
200	50	536 408	6.3
200	100	722 540	53.2
200	150	1 121 910	84.8
200	200	1 399 210	40.3
300	50	609 124	14.5
300	100	934 478	578.7
300	150	1 158 880	513.1
300	200	ML(1 431 036)	319.0
400	50	ML(707 057)	283.6
400	100	ML(1 000 428)	458.0
400	150	ML(1 324 754)	360.0
400	200	1 423 146	414.9
500	50	ML(815 576)	498.9
500	100	ML(1 106 750)	356.9
500	150	ML(1 364 555)	334.4
500	200	ML(1 587 294)	328.5

The numerical results are presented in tables 5 to 7, each one with a different number of COs, cabinets, potential sites to install new cabinets and potential sites to install the micro-nodes per cabinet (i.e., per DSA). In each table, the first column presents the number of new POTS points of demand and column 2 presents the number of new non-POTS points of demand. Column 3 presents the value of the optimal solution or the best solution found by the branch-and-bound algorithm if the memory limit (ML) is reached and column 4, the CPU execution time to find this solution.

From these tables, we note that the CPU execution time of the branch-and-bound algorithm increases dramatically with the number of points of demand and with the number of sites to install the micro-nodes. However, the results show that fair-sized instances can be solved to optimality with 500 MB of memory. 15 out of 60 instances of the problem generated were not solved within this limit. In fact, the proposed approach can be used if the access network planning is done for one or two DSAs (cabinets). Indeed, we have solved instances with up to 5000 customers with two DSAs within 20 sec of CPU times.

Table 7. Numerical results for $|N_O| = 10$, $|N_{J1}| = 10$, $|N_{J2}| = 10$, $|N_M| = 10|N_{J1}|$ and 150 (100 POTS and 50 non-POTS) points of demand (PoD) already connected

New POTS PoD	New non-POTS PoD	OPT Value [$]	OPT CPU [sec]
100	50	466 214	0.8
100	100	618 554	18.4
100	150	871 786	2.3
100	200	1 058 100	4.0
200	50	526 284	3.0
200	100	748 602	78.9
200	150	1 010 164	13.9
200	200	1 238 154	17.6
300	50	620 258	41.7
300	100	812 992	7.0
300	150	1 039 728	820.6
300	200	1 333 576	609.3
400	50	743 552	155.7
400	100	ML(908 958)	492.9
400	150	1 219 824	33.2
400	200	1 394 136	594.0
500	50	850 394	850.2
500	100	ML(1 073 366)	888.7
500	150	ML(1 282 123)	411.2
500	200	ML(1 485 813)	443.2

4 Conclusions and Further Works

In this paper, we have proposed to tackle the multitechnology access network planning problem. Four important access network architectures/technologies are considered: DSL from the CO, FTTN, FTTn and FTTP. The problem has been formulated with an integer mathematical programming model. The numerical results have shown that optimal solutions can generally be found using CPLEX for the size of instances considered.

There are several avenues of research that are open at this point. For instance, in this paper, we considered a model in which the FTTP access network has a star topology. Other topologies are proposed for FTTP [12] and can be included in our model.

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Appendix A

The model for the multitechnology access network planning problem, denoted P, can now be given. P:

$$\min_{\mathbf{u},\mathbf{v},\mathbf{w},\mathbf{x},\mathbf{y}} Z_{DSL-CO} + Z_{FTTN} + Z_{FTTn} + Z_{FTTP} \tag{A.1}$$

Subject to

CO and cabinet capacity constraints

$$\sum_{t \in T_D} u_o^t \leq \kappa_o \quad \forall_{o \in N_O} \tag{A.2}$$

$$\sum_{t \in T_N} u_j^t \leq \xi_j \quad \forall_{j \in N_{J1}} \tag{A.3}$$

Micro-node type uniqueness constraints

$$\sum_{t \in T_M} u_m^t \leq 1 \quad \forall_{m \in N_M} \tag{A.4}$$

DSL loop length constraints

$$x_{o(p),p}(\gamma_{o(p),p} - \eta_p^{c,4,2})\beta_p^c \leq 0 \quad \forall_{c \in C,\, p \in N_{P1}} \tag{A.5}$$

$$x_{j(p),p}(\gamma_{j(p),p} - \eta_p^{c,4,2})\beta_p^c \leq 0 \quad \forall_{c \in C,\, p \in N_{P1}} \tag{A.6}$$

$$x_{m,p}\left(\gamma_{m,p} - \eta_p^{c,4,2}\right)\beta_p^c \leq 0 \quad \forall_{c \in C,\, p \in N_{P1},\, m \in N_M^p} \tag{A.7}$$

Line card capacity constraints (at the loop level) for the DSLAMs and nodes

$$\sum_{p \in N_{P1}: o = o(p)} (\alpha_p + \lambda_{o,p})\, x_{o,p} \leq \sum_{t \in T_O} \phi^{\ell(t)} v_o^{\ell(t)} \quad \forall_{o \in N_O} \tag{A.8}$$

$$\sum_{p \in N_{P1}: j = j(p)} (\alpha_p + \lambda_{j,p})\, x_{j,p} \leq \sum_{t \in T_N} \phi^{\ell(t)} v_j^{\ell(t)} \quad \forall_{j \in N_{J1}} \tag{A.9}$$

DSLAM and node capacity constraints (at the slot level)

$$v_o^{\ell(t)} \leq \chi^t u_o^t \quad \forall_{o \in N_O,\, t \in T_O} \tag{A.10}$$

$$v_j^{\ell(t)} \leq \nu^t u_j^t \quad \forall_{j \in N_{J1},\, t \in T_N} \tag{A.11}$$

Micro-node capacity constraints (at the loop level)

$$\sum_{p \in N_{P1}: m \in N_M^p} (\alpha_p + \lambda_{m,p})\, x_{m,p} \leq \sum_{t \in T_M} \delta^t u_m^t \quad \forall_{m \in N_M} \tag{A.12}$$

Point of demand maximum assignment constraints

$$x_{o(p),p} + x_{j(p),p} + \sum_{m \in N_M^p} x_{m,p} + \sum_{j \in N_J} y_{j,p} = 1 \quad \forall_{p \in N_{P1}} \tag{A.13}$$

$$\sum_{j \in N_J} y_{j,p} = 1 \quad \forall_{p \in N_{P2}} \tag{A.14}$$

FTTP fiber length constraints

$$y_{j,p}\left(\rho_{j,p} - \theta_j\right) \leq 0 \quad \forall_{p \in N_P, j \in N_J} \tag{A.15}$$

Splitter capacity constraints

$$\sum_{p \in N_P} \alpha_p y_{j,p} \leq \mu y_{o(j),j} \quad \forall_{j \in N_J} \tag{A.16}$$

FTTP cabinet constraints

$$y_{o(j),j} \leq \pi_j w_j \quad \forall_{j \in N_J} \tag{A.17}$$

Integrality constraints

$$\begin{gathered} u_o^t \in \mathbb{N},\ u_j^t \in \mathbb{N},\ u_m^t \in \mathsf{B}, \\ v_o^\ell \in \mathbb{N},\ v_j^\ell \in \mathbb{N},\ w_j \in \mathsf{B},\ x_{o(p),p} \in \mathsf{B}, \\ x_{j(p),p} \in \mathsf{B},\ x_{m,p} \in \mathsf{B},\ y_{j,p} \in \mathsf{B},\ y_{o(j),j} \in \mathbb{N} \end{gathered} \tag{A.18}$$

Constraints (A.2) and (A.3) impose the number of DSLAMs (nodes) installed in each CO (at each cabinet location) be less than or equal to the maximum allowed for that CO (cabinet location). Constraints (A.4) are micro-node type uniqueness constraints and they require of installing at most one micro-node type at each site. Constraints (A.5) to (A.7) impose a point of demand connected to a DSLAM, a node or a micro-node to respect the maximum loop length in order to have the specified performance for each class of service. Note that those constraints are not necessary if the proposed preprocessing algorithm is used. Constraints (A.8) and (A.9) are line cards capacity constraints and they require the number of customers (with and without bonding) connected to a DSLAM (node) be less than or equal to the total capacity of the line cards installed in that DSLAM (in that node). Constraints (A.10) and (A.11) impose the number of line cards installed in a DSLAM (node) be less than or equal to its number of slots. Constraints (A.12) are micro-node capacity constraints and they require the number of customers connected to a micro-node be less than or equal to the maximum number of customers that can be connected to it. Constraints (A.13) impose each POTS point of demand to be connected with at most one access link and constraints (A.14) require each non-POTS point of demand to be connected to at most one splitter. Since constraints (A.13) and (A.14) are inequality constraints, a point of demand can be not connected to the network and, in that case, a penalty cost will be considered in the objective function. Constraints (A.15) impose a point of demand connected to the FTTP network to respect the maximum fiber length (power budget). Note that those constraints are not necessary if preprocessing is used. Constraints (A.16) are splitter capacity constraints and constraints (A.17) impose the number of splitters installed at a cabinet location, be less than or equal to the maximum number of splitters that can be installed in that location. Finally, constraints (A.18) are the variable integrality constraints.

It should be pointed out that constraints (A.16) and (A.17) impose the FTTP network to have a star access network topology. Other topologies can be considered by the network planner and the proposed model can be adapted accordingly, for instance, the multiple-tree access topology. In that case, the fibers are installed from the COs to primary optical splitters located at cabinet locations and those splitters are connected to secondary splitters located in the field. Some papers have been published on that problem, for instance, see [14,15,16].

Note that P is NP-hard (transformation from the capacitated facility location problem [13]).