Advanced Dynamic Migration Planning toward FTTH

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ABSTRACT

This article proposes a dynamic migration planning methodology for communication networks. Aimed at providing optimal technical performance, the approach takes into account dimensioning of network infrastructure and services, as well as evaluation of revenues and costs. As a result, the migration planning method provides a cost-effective network deployment plan based on an optimal stepwise upgrade strategy. Market information, existing infrastructure, costs, and demand forecasting are then considered in order to determine this strategy by solving a combinatorial optimization problem. It is described theoretically, and a techno-economic evaluation framework is introduced to assess its financial feasibility. The model is a suitable guideline to tackle migration problems commonly solved by using anticipated, single- ,and multi-period planning techniques. Considering a particular example, a study on migration toward fiber to the home is analyzed. Fiber to the cabinet/building architectures are then proposed as possible intermediate steps in the migration path to fiber to the home. Finally, a case study for an existing access network is analyzed.

INTRODUCTION

The migration of a telecommunication network can be approached as a multi-period planning problem. Its solution involves demand forecasting, dimensioning of network infrastructure and processes, as well as evaluation of their economic costs. The resulting upgrade plan is a network deployment strategy that defines a stepwise migration path, which is a temporal sequence of network layouts called migration steps.

Network migration also entails careful evaluation of revenues, capital (CAPEX) and operational expenditures (OPEX). Hence, the upgrade plan specifies what investments are required at each point in time. Specifically, the CAPEX needed to upgrade the network from one migration step to another as well as annual OPEX contributions are part of the solution. Therefore, the best deployment plan is the one that minimizes the total cost of ownership (TCO) while guarantying optimal technical performance.

Dynamic migration is useful for multi-period planning of core and wireless/wireline access networks. For instance, operators face the challenge of upgrading their networks to bring fiber and high-speed wireless to their customers. In particular, fiber-based access has become essential to provide multimedia services that demand high quality standards. This has forced operators to focus their efforts on the promotion of models to assess financial feasibility for fiber deployment. This goal can be achieved by temporarily deploying hybrid fiber-copper fiber to the cabinet/building (FTTC/B) solutions on the migration path to fiber to the home (FTTH). As strategy, this exploits the unused potential transmission capacity of installed copper lines while optimizing costs and profitability.

This article presents a generalized model to study network migration problems. As an example, the approach is defined to analyze technical and financial feasibility for migration toward FTTH. The framework studies vertically integrated operators, who are those providing both services to end customers and network connectivity (i.e., layer 2 (Ethernet) and layer 3 (IP) access) to service providers [1]. The analysis is focused on target migration areas that can comprise dense urban (DU), urban (UR), and rural (RU) area types. Each area may connect customers classified as single-family units (SFUs), multi-dwelling units (MDUs), and business dwelling units (BDUs). Moreover, network dimensioning and cost modeling are performed based on the services bought by customers and the operator's existing infrastructure. In order to achieve its goal, the migration planning model defines full copper, FTTC/FTTB architectures as steps on the transition to FTTH.

This article is organized as follows. We study the generalized dynamic migration strategy. We describe the techno-economic framework for migration planning. We define a

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model for migration planning toward FTTH. We present a case study, and finally conclude the article.

Generalized Dynamic Migration Planning

Generalized Migration Model

The goal of migration planning is to upgrade an existing infrastructure to a target network architecture. However, direct migration is not always feasible due to the high costs involved. A solution would then be to implement network architectures that gradually outperform the infrastructure's capabilities.

If we model a migration step as a state s defining a network architecture, an upgrade plan is simply a temporal sequence of states that configure a migration path. As discussed in [2], this problem can be tackled by introducing a set of S states [1, 2, …, s, …, S], with state S representing the target network layout. For this set, Fig. 1a illustrates a state diagram that depicts all possible forward transitions between migration steps.

In general, a network infrastructure may be heterogeneous, which means that it consists of several coexisting architectures. Thereby, any existing network might define a layout of $S - 1$ initial states or conditions $x \in [1, \ldots, S - 1]$. Given this hybrid design, how do we determine its optimal upgrade plan toward S?. The first step is to establish candidate migration paths, which are derived for each initial condition x from the state diagram. We can model these paths as rows of a binary migration matrix $\boldsymbol{M}$, whose structure is shown in Fig. 1b. It has S columns, each one referring to a state. The matrix element $M_{i,j} \in \{0,1\}$, indicates whether the state defined by the jth column is visited, $M_{i,j} = 1$, or not, $M_{i,j} = 0$, by a network following the ith path. Therefore, this ith candidate migration path is an S-dimensional row vector whose first nonzero element is x, since backward transitions are not allowed. On the other hand, $\boldsymbol{M}$ has W rows that represent the candidate paths of all the $S - 1$ initial conditions. As a result, $\boldsymbol{M}$ contains all the possible migration paths of a heterogeneous network infrastructure that connects subscribers within a service area.

A migration path consists of S holding time intervals T_s, $s \in [1, \ldots, S]$, where T_s is the time in years the network stays at the architecture defined by state s. For every candidate path, we can define a vector $\boldsymbol{T_{hold}} = (T_1, T_2, \ldots, T_{S-1}, T_s)$, with each component representing a holding time T_s. As an example, Fig. 1c depicts a migration path with initial condition $x = 1$ and $\boldsymbol{T_{hold}} = (T_1, 0, T_3, 0, \ldots, 0, T_{S-1}, T_S)$. Given a migration period T_{Mig}, in the second step, a techno-economic evaluation of the problem is made. Its goal is to determine, per existing initial state x, both the path and its corresponding $\boldsymbol{T_{hold}}$ that minimize costs and maximize profit. Therefore, for the most general case, the network deployment plan must define $S - 1$ optimal paths. This optimization and evaluation process is discussed in detail in the next section.

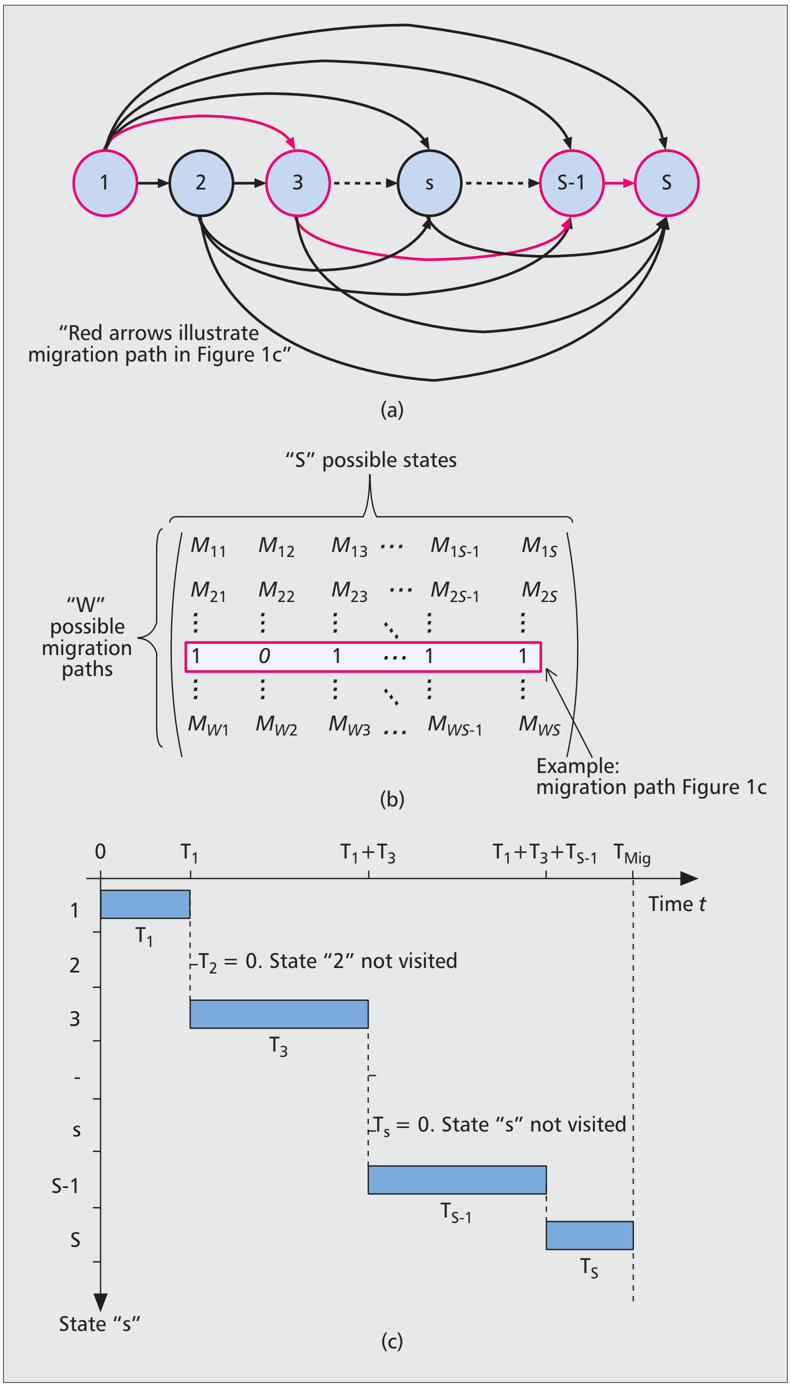

Figure 1. *a) Generalized migration state diagram; b) generalized migration matrix* $\mathbf{M}$*; c) illustration of a migration path from state* $x = 1$ *to the target state S subject to migration period* T_{Mig} *and holding times* T_s.

Techno-Economic Framework for Dynamic Migration Planning

Given a target architecture S, a set of migration steps, and $S - 1$ initial conditions, migration planning toward S can then be formulated as a combinatorial optimization problem. It is solved via an exhaustive search method, which is implemented using the techno-economic framework shown in

Fig. 2. It comprises definition of input information, revenue and cost modeling, network and service dimensioning, as well as evaluation [3].

Objective Function and Constraints

The best upgrade plan is defined by the migration paths that yield maximal profitability at minimum cost. For a network segment with initial condition x, its objective function is then the profit, which is the total revenue minus the TCO. In general, this TCO is the sum of the OPEX and CAPEX contributions from all visited states in the migration path. Thus, given a forecast interval and a planning horizon of length T_{Mig}, the following constraints apply for every candidate path in $\boldsymbol{M}$:

- For each component T_s of $\boldsymbol{T_{hold}}$, if state s is not visited, $T_s = 0$; otherwise, T_s must fulfill $T_{\text{Min}} \leq T_s \leq T_{Mig}$. The parameter T_{Min} represents the installation time needed to deploy capacity when a migration occurs. Additionally, T_s is assumed to be a positive integer.
- The sum of the vector components of $\boldsymbol{T_{hold}}$ must equal T_{Mig}.

Definition of Input Information

The goal is to upgrade an existing heterogeneous network; therefore, its relevant input information is defined and processed as follows:

- Market information such as existing customer types and the services offered to them is collected.
- Service areas, their number of connected users per customer type, and traffic demands are determined.
- The existing network infrastructure is described. It gives a detailed view of installed architectures, their technologies, and number of connected users. This information defines user groups with common initial condition x. Therefore, for the subscribers belonging to a customer type within a service area, a matrix $\boldsymbol{M}$ is set up to list the candidate paths of the existing initial states x. The following section explains how this is modeled for migration toward FTTH.
- Price books are used as input for both CAPEX/OPEX and revenue calculation.
- Migration analysis uses expected evolutions of traffic demands and costs to find the optimal upgrade strategy. Therefore, a forecast interval equal to T_{Mig} is set up to make these predictions. Also, T_{Min} is fixed as a constant input parameter.

For each existing user group with initial condition x, the set of vectors $\boldsymbol{T_{hold}}$ per candidate path that fulfill the constraints are calculated. Thereby, both these candidate paths and $\boldsymbol{T_{hold}}$ vectors define the search space of the optimization problem.

Dimensioning, Modeling, and Evaluation

The members of a user group with initial condition x, within a matrix $\boldsymbol{M}$, are simultaneously migrated following the same path. The objective function of the group is optimized by sequentially selecting from the search space a candidate path. Thus, for every existing user group with initial condition x, the following analysis is made on each candidate vector $\boldsymbol{T_{hold}}$ of the selected path:

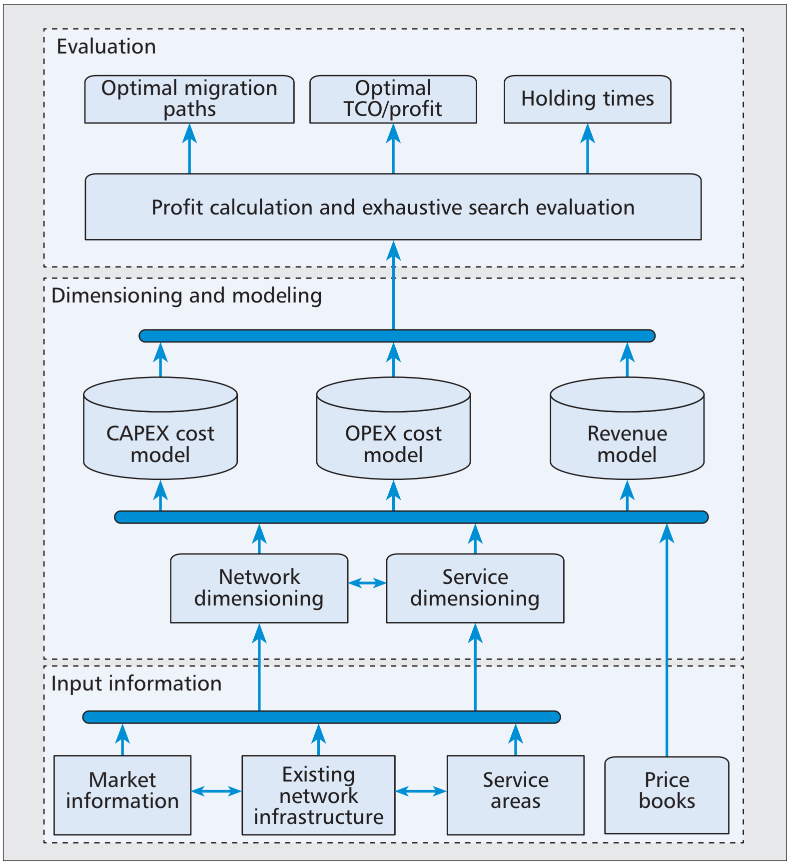

Figure 2. *Techno-economic framework for dynamic migration planning.*

- Network component costs and traffic demand predictions are calculated over the forecast interval. For the candidate path, the network dimensioning module reads out both the corresponding matrix row and $\boldsymbol{T_{hold}}$ from left to right. Whenever a state transition occurs, based on predicted demands, dedicated dimensioning is used to calculate the infrastructure required to visit the next state.
- The CAPEX model, for each state transition in the path, calculates the costs to buy, upgrade, and install the infrastructure. The total CAPEX is the sum of the contributions at all migration steps over T_{Mig}.
- The OPEX model calculates the costs to keep the network operational. Following [4], these costs include service provisioning, operational network planning, marketing, renting, energy consumption, maintenance and reparation, as well as pricing and billing. For each visited state s, the model calculates the annual OPEX contributions over the corresponding component T_S of $\boldsymbol{T_{hold}}$. The total OPEX is the sum of the contributions at all steps.
- The revenue model estimates income based on predetermined service types. These are defined according to the technical capabilities needed to run a service on the network. Thus, the product portfolio of the operator is mapped to these service types. When a state transition occurs in the path, service dimensioning calculates the potential cover-

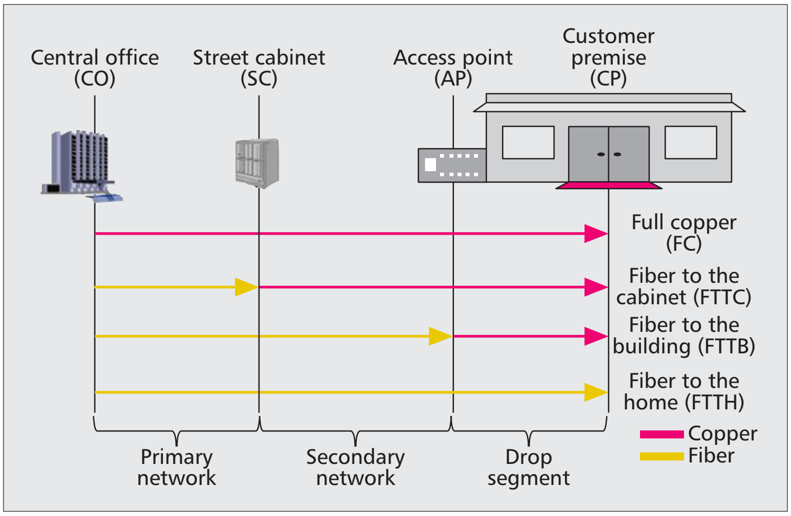

Figure 3. *FTTx architectures.*

age for each service. The reason is that any architecture performs differently for each service; thus, the better the coverage, the higher the service type that can be provisioned on the network. The model predicts the number of users in the group who upgrade their services due to network migration. Consequently, using the pricing defined per service type in the price books, the total revenue is calculated as the sum of the income contributions from the users at all steps over T_{Mig}.

Once all the candidate solutions are selected and analyzed, the evaluation phase calculates per candidate path and $\boldsymbol{T_{hold}}$ the total profit. The path and its corresponding $\boldsymbol{T_{hold}}$ that maximize profitability are selected as the optimal upgrade plan. The solution vector $\boldsymbol{T_{hold}}$ schedules the migration of the group, and dictates what investments are made at each point in time. Furthermore, the optimal path explicitly defines the type of architecture to deploy at each step. As an example, in the following section the generalized model is defined for dynamic migration toward FTTH.

Dynamic Migration Planning toward FTTH

This section formulates the migration planning model toward FTTH for fixed broadband access networks. The architectures and technologies used to implement them are introduced in order to define the migration steps.

FTTx Network Architectures

Fixed broadband access networks are made up of fiber, copper, coaxial cable, and power line solutions. The most popular scenarios are based on either hybrid fiber-copper or full-fiber oriented deployments. These variants define the FTTx architectures shown in Fig. 3, which mainly differ on how far the optical fiber goes.

Unlike full copper (FC) and FTTH architectures, FTTC/B represent hybrid optical-copper access networks. These hybrid solutions implement optical networks from central offices (COs) to remote nodes located in the outside plant. These nodes are street cabinets (SCs) and access points (APs) for FTTC and FTTB, respectively. From these nodes, copper networks are rolled out to span customer premises equipment.

Recently, fiber to the distribution point (FTTDp) or fiber to the street (FTTS) has been proposed to shorten the last copper segment to end users. Furthermore, fiber to the desktop is trying to extend the FTTx concept to an in-house fiber solution. In order to keep the model simple, these cases have not been included in the presented version. Therefore, our model only considers FC and FTTC/B as intermediate migration architectures.

Copper-Based Access Network Technologies

The copper-based segment of FC/FTTx architectures can be implemented with digital subscriber line (DSL) technologies, which connect DSL access multiplexers (DSLAMs) to modems installed at customer premises. The most common variants are asymmetric DSL2+ (ADSL2+) [5] and very high speed DSL2 (VDSL2) [6], which with vectoring or phantom mode can increase their capability for the same copper drop segments, but with some limitations [7]. As an alternative to DSL, the Data over Cable Service Interface Specification (DOCSIS) provides high-speed transmission capacity over existing hybrid fiber-coaxial (HFC) networks [8].

Fiber-Based Access Network Technologies

Fiber-based networks represent the optical segment of FTTx architectures, and can be deployed using active or passive optical network (AON/PON) technologies. Nowadays, as shown in [9], next generation optical access (NGOA) targets longer distances and higher transmission bandwidths with solutions such as gigabit PON (GPON), wavelength-division multiplexing (WDM) PON, hybrid PON, next generation PON version 2 (NG-PON2), and active optical Ethernet. These technologies allow wise integration with copper-based solutions.

Migration Planning toward FTTH

Migration toward FTTH is modeled by defining the target state as $S = FTTH$. If we consider greenfield (G) subscribers (i.e., users who need complete installation of infrastructure), migration can be studied using five states: greenfield (G), FC, FTTC (C), FTTB (B), and FTTH (H). Thereby, any state $s \in [G, FC, C, B, H]$ and there may be four initial conditions $x \in [G, FC, C, B]$.

The subscribers are within a target migration area that may span a country, state, city, or small town. This area may include DU, UR, and RU area types, or service areas, which are defined by their user densities (customers per square kilometer). In general, each of these areas serves three customer types: SFU, MDU, and BDU. For the users belonging to a customer type within an area type, let us define a five-state diagram and its 15×5 migration matrix $\boldsymbol{M}$ as shown in Figs. 4a and 4b, respectively. Furthermore, let us divide these users into four groups, each one containing subscribers with a common initial condition x. As shown in Fig. 4b, each user group within an area type has a limited number of possible migration paths, which indeed depends on its initial condition x. The state diagram determines for each state x the candidate migration paths (rows) in $\boldsymbol{M}$. Therefore, the members of a user group can simultaneously be migrated to FTTH following the same migration path over a planning horizon T_{Mig}.

From the previous analysis, for a target migration area covering DU, UR, and RU area types, each one serving SFU, MDU, and BDU users, the generalized migration planning model toward FTTH is defined as:

- There are 3 area types × 3 customers types per area = 9 migration matrices $\boldsymbol{M}$.
- There are 3 area types × 3 customers types per area × 4 user groups per customer type = 36 migration paths, user groups, and initial conditions x.
- For a user group within an area type with initial condition x equal to G, FC, C, or B, there are 8, 4, 2, or 1 candidate migration paths, respectively (Fig. 4b).

The starting network layout may be heterogeneous because the states x define several FC/FTTx coexisting architectures. Additionally, for the generalized problem, the goal is to independently migrate 36 user groups by finding 36 optimal migration paths. Nonetheless, the model can be adjusted to study simpler scenarios by just removing matrices and/or rows that represent nonexistent service areas and/or user groups.

In order to find the migration plan, the techno-economic framework follows the steps explained in the previous section. However, for the sake of clarity, in the definition of input information, DU, UR, and RU service areas as well as their number of SFU, MDU, and BDU users must be determined. Besides, a 15 × 5 migration matrix $\boldsymbol{M}$ is set up for each customer type within an area type. The existing user groups per matrix and their initial states x are defined. Moreover, for each migration step, the network dimensioning module calculates the components in central offices, street cabinets, access points, as well as cabling. Furthermore, the revenue model defines five service types:

- Service type 1: VoIP and narrowband internet
- Service type 2: triple play (broadband internet, VoIP, TV)
- Service type 3: broadband Internet, VoIP and high definition television
- Service type 4: broadband Internet, VoIP, high definition television, and interactive services
- Service type 5: Carrier class profile, which provides layer 2 and layer 3 bitstream access, at high speeds, to service providers

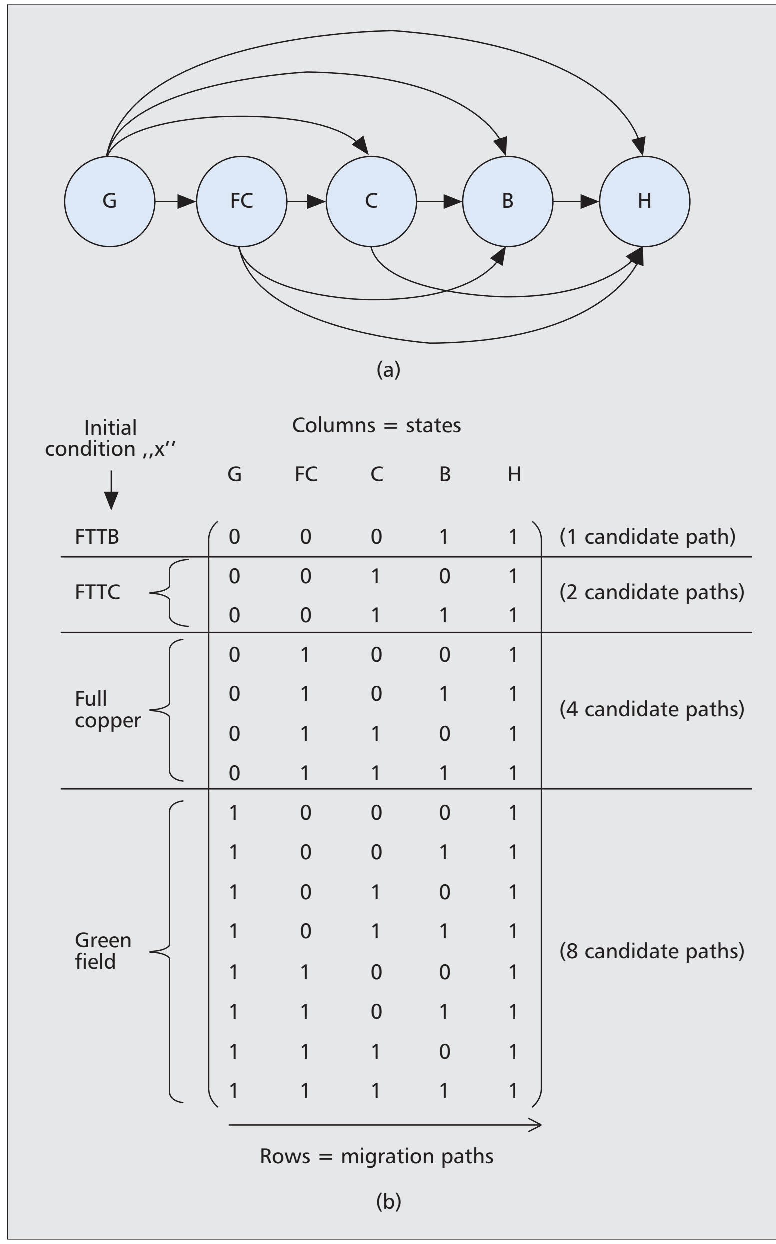

Figure 4. *a) Five-state diagram for migration towards FTTH [2]; b) migration Matrix for users belonging to a customer type within an area type.*

Case Study

Case Definition

Let us study migration toward FTTH for an operator in the city of Bogotá D.C., Colombia. Relevant input information is [10]:

- A DU area of 477.8 km^2 serves 504,783 subscribers with FC and FTTC installed architectures.
- An RU area of 1298.2 km^2 serves 1126 subscribers with FC installed architecture.
- Due to the density of population, there is no UR area.
- FC solutions are point-to-point ADSL2+ copper networks. On the other hand, FTTC is a point-to-multipoint (P2MP) network implemented with GPON/VDSL2 technologies. It uses fiber rings that offer protection at the primary network segment shown in Fig. 3.

Columns 1 to 5 in Table 1 detail how users are distributed per area and customer type as well as per initial condition x. With this input information, let us use GPON/VDSL2 technologies to dimension the FTTx architectures with protected primary network segments. Therefore, in the end, the goal is to reach a GPON-based FTTH solution. This problem requires six migra-

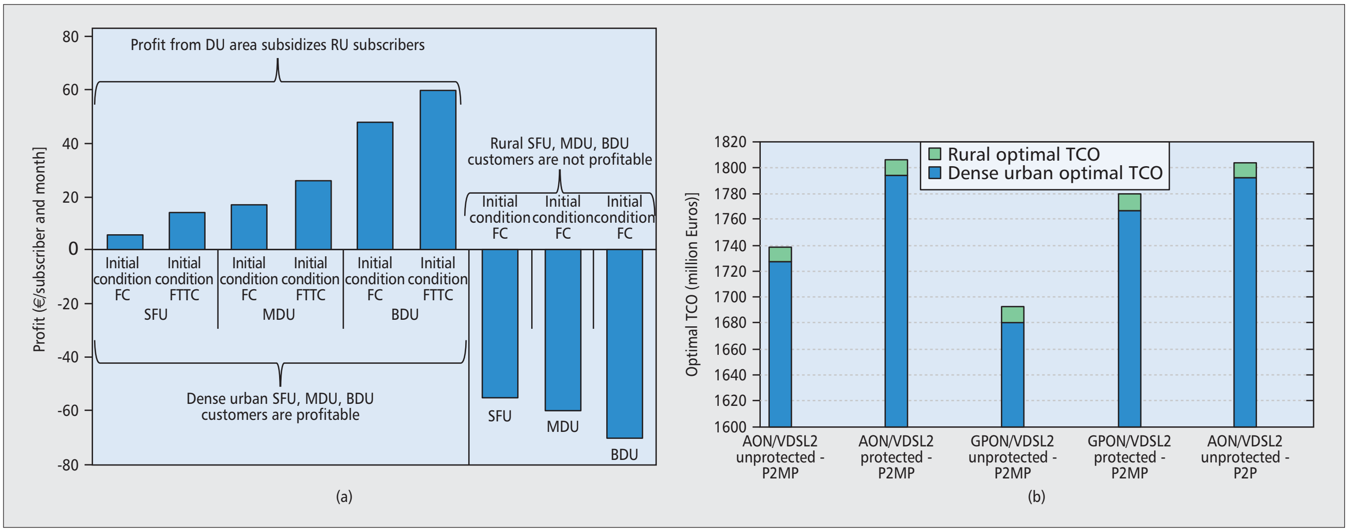

Figure 5. *a) Average profit per user and month; b) optimal TCO for migration alternatives.*

tion matrices ***M***, three for each existing area type, and thus one per customer type. Moreover, there are six and three user groups within the DU and RU areas, respectively. Considering T_{Mig} = 10 years, $T_{\min}$ = 1 year, the techno-economic framework is used to determine the optimal upgrade strategy.

Results and Analysis

Columns 6–11 in Table 1 present the optimal migration paths along with their holding times $\boldsymbol{T_{hold}}$. Additionally, columns 12–14 show the optimal accumulated profits, revenues, and TCO per user and month calculated over T_{Mig}. From column 12, we see that the operator profits from DU users, which means that their monthly generated revenue (column 13) is higher than the cost (column 14) to migrate them toward FTTH. Therefore, there are six optimal paths in the DU area. Nonetheless, the RU area is unprofitable, since the average monthly TCO is not compensated by the revenues from its users; thus, migration is not feasible. The three $\boldsymbol{T_{hold}}$ vectors shown in Table 1 for the RU area only represent the holding times that lead to minimum loss. Profitability can then be achieved by increasing revenues and/or decreasing the TCO.

Increasing the prices of the services offered to RU users by the amount necessary to compensate for the profit deficit is not a solution to reach profitability in this case. By checking the worst case in Table 1, the monthly revenue from a rural BDU should be increased by at least €70/month to compensate for a €101/month cost. Increasing revenues by only raising prices affects market growth. Nevertheless, if the objective of the operator is to achieve, instead of profit, coverage without losses, profitable DU customers can subsidize RU users, as shown in Fig. 5a. Cross subsidy reduces the investment deficit, and has to be complemented with business and marketing strategies that encourage customers to upgrade their services to the highest service type they can buy.

In order to decrease TCO, we can study how migration costs change by considering alternative pairs of optical/copper technologies. Therefore, let us define four additional alternatives to implement our FTTx architectures:

- P2MP unprotected access network implemented with GPON/VDSL2
- P2MP protected access network implemented with AON/VDSL2
- P2MP unprotected access network deployed with AON/VDSL2
- Point-to-point unprotected access network implemented with AON/VDSL2

Figure 5b shows the TCO obtained for each alternative using the techno-economic framework. Although less tolerant to failures, unprotected solutions are cheaper than their protected counterparts. But in fact, this makes these deployments inadequate for massive markets, since penalties due to service unavailability impact profitability. Furthermore, it can be seen that the TCO of GPON solutions is cheaper than the counterparts based on AON Ethernet. This illustrates the advantage of PON solutions due to their low energy consumption. Therefore, the initial P2MP protected access network deployed with GPON/VDSL2 is the best choice as it increases availability, and in the long run is cheaper than AON alternatives.

The TCO needed to migrate an RU subscriber is high, since rural installations require more effort in terms of infrastructure deployment, fiber trenching, and maintenance and repair. Besides, in most cases, it is difficult to increase user adoption rates in RU areas with low densities. Therefore, providing coverage and services to this type of territory is normally not an appealing issue for operators. From this discussion, it follows that in general a migration strategy must be aware of these key points:

- Profitability can be achieved by reducing costs. The adoption of technologies with high technical performance and low CAPEX and OPEX in the long run is an alternative solution. Therefore, good knowledge of both the quantitative impact of technologies on network costs and their main cost drivers is required.
- Suitable marketing strategies and pricing rules, aimed at producing higher revenues, can increase user adoption rates. This

Area type	Customer type	Initial state x	Distribution of subscribers	Number of subscribers	Optimal migration path	Holding times T_{Hold} (years)					Optimal profit (€/user) monthly	Revenue profit (€/user) monthly	Optimal TCO (€/user) monthly
						T_G	T_{FC}	T_C	T_B	T_H			
Dense urban	SFU	FC	99%	164,960	FC → FTTC → FTTH	0	2	6	0	2	6	37	31
		FTTC	1%	1830	FTTC → FTTH	0	0	8	0	2	15	45	30
	MDU	FC	99%	245,388	FC → FTTC → FTTB → FTTH	0	2	4	2	2	17	40	23
		FTTC	1%	2722	FC → FTTB → FTTH	0	0	6	2	2	26	48	22
	BDU	FC	74%	66,590	FC → FTTC → FTTH	0	2	6	0	2	49	91	42
		FTTC	26%	23,293	FTTC → FTTH	0	0	8	0	2	60	101	41
Rural	SFU	FC	100%	787	Negative profit	0	4	2	0	4	–55	32	87
	MDU	FC	100%	139	Negative profit	0	6	2	0	2	–61	30	91
	BDU	FC	100%	200	Negative profit	0	4	4	0	2	–70	31	101

Table 1. *Optimal migration strategy for the case study.*

encourages subscribers to upgrade their services, and lures potential customers to connect to the network.

- Cross subsidies between users can propel migration to FTTH in areas with profit deficit. This is a solution only if optimal profitability is not a concern for operators.

Migration toward FTTH cannot always be feasible. Hence, the proposed migration approach could be extended to study target states $s \in [G, FC, C, B, H]$ in order to determine the best final state S per user group. This would allow a better and more generalized definition of the optimal network deployment plan.

Conclusions

The generalized migration planning model suggests a stepwise upgrade approach. It determines an optimal network deployment plan that maximizes profit while guaranteeing technical performance. We have shown that the calculation of this plan includes a techno-economic analysis that comprises service and network dimensioning, as well as evaluation of revenues and costs. In particular, the generalized model is formulated for migration toward FTTH. This example shows that an accurate definition of the migration steps is mandatory to tackle the network migration problem properly. We discuss a case study which illustrates that migration is not always feasible. Although profitability can be achieved by increasing revenues and/or decreasing the TCO, we show that migration could be possible if, instead of profit, the objective is to achieve coverage without losses. Hence, profitable users can subsidize unprofitable areas. The analysis shows that any migration strategy has to be aware not only of the technical but also the economic constraints of the problem to be solved.

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Biographies

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