BROADBAND ACCESS NETWORK PLANNING OPTIMIZATION CONSIDERING REAL COPPER CABLE LENGTHS

SUMMARY Broadband access network planning strategies with techno-economic calculations are important topics, when optimal broadband network deployments are considered. This paper analyzes optimal deployment combination of digital subscriber line technologies (xDSL) and fiber to the home technologies (FTTx), following different user bandwidth demand scenarios. For this reason, optimal placement of remote digital subscriber line multiplexer (RDSLAM) is examined. Furthermore, the article also discusses the economy of investments, depending on certain investment threshold and the reach of different xDSL technologies. Finally, the difference between broadband network deployment in a characteristic urban and rural area in Republic of Slovenia, in terms of required optical cable dig length per household is shown. A tree structure network model of a traditional copper access network is introduced. A dynamic programming logic, with recursion as a basis of a tree structure examination and evaluation of optimal network elements placement is used. The tree structure network model considers several real network parameters (e.g.: copper cable lengths, user coordinates, node coordinates). The main input for the optimization is a local loop distance between each user and a candidate node for RDSLAM placement. Modelling of copper access networks with a tree structure makes new extensions in planning optimization of broadband access networks. Optimization of network elements placement has direct influence on efficiency and profitability of broadband access telecommunication networks.

Key words: broadband, copper network, remote DSLAM, xDSL, FTTx, optimization, tree structure, dynamic programming

1. Introduction

Next generation broadband services evolution (e.g.: IP TV, high definition TV, video on demand, video streaming, IP telephony) and consequently much higher user bandwidth demands, are the main drivers for fixed operators to deploy high speed broadband access networks. The traditional asymmetric digital subscriber line technology (ADSL) with less than 8 Mbit/s download channel capacity, has become inappropriate for the next generation users (Okumura, 2007 [1], Carpenter, 2001 [2]). Development of very high bit rate digital subscriber line technologies (VDSL) is one of the solutions how to deliver a high-bandwidth capacity to end users. The main drawback of various fiber access network solutions is the return of investment (ROI).

Deployment of access network with certain combinations of xDSL and FTTx technologies may be optimal, considering short range of VDSL and VDSL2 technologies, and vast investment needed for point to point fiber to the home solution (PtP FTTH). In the paper, the FTTH abbreviation is used to indicate point to point FTTH technical solution (e.g. active optical network (AON)). If the VDSL technologies are used for delivering high-bandwidth capacity through the last kilometer of existing copper lines, and optical fiber lines are required only for the RDSLAMs, the investment in the optical fiber dig length can be reduced and the performance of VDSL technologies can meet the needs of end users, as shown in Fig 1.

For optimal access network planning with combination of xDSL and PtP FTTH technologies and reuse of existing copper network, the existing copper network and end users in the target area have to be simulated. Different methods can be used to find optimal RDSLAM placement in the access network, generally the knowledge of dynamic programming is applied. Several projects deal with simulation of existing copper network, but do not propose optimal RDSLAM positions [5], [6], [7]. Their focus is on techno-economical comparison of various broadband access technologies deployment combinations, based on statistical user density presumptions. Different methods for cable and duct lengths modelling are proposed (e.g.: star topology, double star topology) [5], [6]. In this paper, the real copper cable lengths are used in computational comparisons. Node placement and sizing for copper broadband access networks with two real examples is analyzed in detail (Carpenter, [2]). The advantage of the proposed method is real input data.
with existing copper network considered. The cost-benefit analysis is carried out only for certain RDSLAM infrastructure without considering optical dig lengths from the central office to the RDSLAM position. Moreover, the method is inappropriate for analyzing FTTH solution.

In this paper, a different method is used for network simulation – graph theory application [8], which is up to certain extend appropriate also for FTTH solution analyses. The economy of investment is calculated in terms of required optical fiber dig length to the RDSLAM, while cables, ducts and the civil work represent the main part of the capital expenditure (CAPEX). Estimation of planned optical fiber dig length per user is the key factor for comparison of investments in urban and rural areas, as shown in next chapters of this paper.

2. Copper Access Network Tree Structure

A traditional copper cable access network (CAN) typically has a tree structure architecture, where the root of the tree represents a central office (CO), vertexes represent joints (J) in a multi-pair copper cable network and leaves represent distribution points (DP). A multi-pair copper cable access network is called local cable network (LCN). Copper cables between distribution points and users (U) make a distribution network (DN). To summarize, the cable access network (CAN) consists of the following of two parts, as shown in Fig. 2:

- the local cable network (LCN) and
- the distribution network (DN).

3. Optimization Methodology

Optimization tree access network model is implemented with Wolfram Research Mathematica version 6.0.0. For tree structure characteristic operations (e.g.: Breadth-First Search and SetGraphOptions) the Combinatorica extension to Mathematica is used [8], [9]. Calculations have been running on the Intel Pentium 4 personal computer with 3 GHz CPU and 1 Gbit RAM.

A tree is a connected graph with no cycles. A graph is a set of vertexes with a set of edges, where each edge is defined by a pair of vertexes [8]. Basic graph characteristics are edge weights, vertex weights and edge directions. A cable access network (CAN) is an undirected graph, a tree with the edge and vertex weights.

Edge weights are distances between joints in a local cable network (LCN). Vertex weights have to be dynamically calculated during the optimization process, and are represented with a vector notation as follows:

\[ J_i = \{x, y, i, o\}, \]

where \( J_i \) represents the joint with a label \( i \), \( x \) and \( y \) are coordinates of the joint \( i \), and \( o \) is an optional set of parameters, which are attributes of the joint \( i \). The optional parameters are calculated dynamically, during tree elements traversal, and are key factors for optimization (e.g.: maximal cable distance from the joint \( i \) to belonging users, number of users belonging to the joint \( i \) and statistical estimation of their generated traffic).

Optimization algorithm runs in two steps. In the first step a Breadth-First Search (BFS) algorithm is used for calculation of all optional parameters [8]. The BFS algorithm also gives us a list of joint labels, \( i \), in the order they have been visited. This order is of a great use in the second step of optimization.

The second part of optimization is based on dynamic programming solution with bottom-up approach [8]. Comparison of joint vectors, recalculation of optional parameters and decision-making if a RDSLAM will be placed at a certain joint in a characteristic fragment of a tree (see Fig. 3), is recursively repeated until the root (CO) of the tree is reached. If the order, in which joints were visited in the first part of optimization is used, it is assured that all children vertexes are visited before their parent vertex. This is the crucial point of the optimization – the information between all children vertexes and a parent vertex has to be transferred before recursion step is made and the parent vertex becomes a child of another parent in lower level of a tree.

Decision-making if a RDSLAM will be placed at certain joint position in the tree, depends on thresholds which are chosen by application user. Thresholds, which can be chosen, are the reach of a xDSL technology and the investment threshold. The reach of the xDSL technology is expressed in meters of cable length (\( R \)). The investment
threshold is expressed by the number of potential users, which are required for acceptable economy of investment \((N)\). A RDSLAM is placed at a certain joint if both thresholds are exceeded.

\[
\begin{align*}
J_i &\quad J_k &\quad J_m \\
\quad &\quad d_{i,k} &\quad d_{m,k} \\
(j+1)^{th} \text{ level} &\quad j^{th} \text{ level}
\end{align*}
\]

Fig. 3 Characteristic fragment of a tree.

Assuming that a RDSLAM is placed at the position of the joint \(m\) (see Fig. 3), the RDSLAM »covers« \(n_m\) belonging users with the maximal belonging user distance \(r_m\). Also threshold conditions are assumed:

\[
\begin{align*}
r_m &\geq R, \\
n_m &\geq N.
\end{align*}
\]

In general, optional parameters of the parent joint \(k\) are recalculated, following the equations below:

\[
\begin{align*}
J_{k_{\text{rec}}} &= \{x, y, k, r_{k_{\text{rec}}}, n_{k_{\text{rec}}}\}, \\
o_{k_{\text{rec}}} &= (r_{k_{\text{rec}}}, n_{k_{\text{rec}}}), \\
r_{k_{\text{rec}}} &= \max(r_i + d_{i,k}, r_m + d_{m,k}, r_k), \\
n_{k_{\text{rec}}} &= n_i + n_m + n_k,
\end{align*}
\]

where \(\text{rec}\) denotes recalculated parameter.

If a RDSLAM is placed at the position of the joint \(m\) (see Fig. 3), optional parameters »maximal belonging user distance« \((r_m)\) and »number of belonging users« \((n_m)\) of the joint \(m\) are put to zero. Afterwards, the recalculation is made, following equations:

\[
\begin{align*}
r_m &= 0, \\
n_m &= 0, \\
d_{m,k} &= 0, \\
r_{k_{\text{rec}}} &= \max(r_i + d_{i,k}, r_k), \\
n_{k_{\text{rec}}} &= n_i + n_k.
\end{align*}
\]

After the recalculation is made, the joint \(k\) becomes a child of another parent. The recursive calculations are repeated until the root (CO) of the tree is reached.

The basic result of optimization is a list of RDSLAMs with belonging co-ordinates, the »covered« user number and the maximal user distance for every RDSLAM. As an additional result of optimization, estimations, like user traffic load at the RDSLAMs positions and dig length from the central office to the RDSLAM positions, are made. These additional estimations are key factors for techno-economic calculations of different FTTx deployment scenarios.

3.1 Input Parameters

General input parameters for the optimization model are as follows:

- the co-ordinate of the central office (CO),
- co-ordinates of joints (J),
- co-ordinates of distribution points (DP),
- co-ordinates of users (U),
- cable lengths between neighbouring vertexes in the tree (CO, J, DP),
- the investment threshold (N) and
- the reach of xDSL technologies (R).

Coordinates and cable lengths for characteristic copper cable access networks have been provided by Slovenian national operator, Telecom Slovenia [10]. Calculations are made for several different investment thresholds and different reaches of xDSL technologies. Available broadband bandwidth as planned at certain household can be directly mapped from the diagram (see Fig. 4). If the length of the household copper local loop is known, the available broadband bandwidth can be estimated for different xDSL technologies, as shown in Fig. 4.

![Reach of xDSL technologies.](image)
Additional input parameters are as follows:

- statistical presumptions of the offered user traffic and broadband penetration estimation.

Post and Electronic Communications Agency of the Republic of Slovenia reports [11], Statistical Office of the Republic of Slovenia [12] and Annual Report of Telecom Slovenia Group [10] are used for statistical presumptions of offered user traffic and broadband penetration estimation. Table 1 shows the additional input parameters, which are used in optimization process. It is defined that a high speed internet service (HSI) is “always-on” broadband connection for Internet browsing, with the average 1.012 kbit/s downlink speed and 256 kbit/s uplink speed. IP telephony and IP TV are considered as services, running over xDSL technology.

### Table 1: Additional input parameters.

<table>
<thead>
<tr>
<th>Input</th>
<th>Percentage of households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total broadband penetration</td>
<td>45.0 %</td>
</tr>
<tr>
<td>xDSL technology penetration</td>
<td>32.3 %</td>
</tr>
<tr>
<td>HSI service</td>
<td>32.3 %</td>
</tr>
<tr>
<td>IP telephony service</td>
<td>7.7 %</td>
</tr>
<tr>
<td>IP TV service</td>
<td>5.4 %</td>
</tr>
</tbody>
</table>

Statistical presumption of the offered traffic for characteristic household is made, as shown in Table 2. It is considered that an average household uses one IP TV service with an average bit rate 5 Mbit/s, one IP telephony service (codec G.711) with an average bit rate 115 kbit/s. Oversubscription factors for IP telephony service and best effort (BE) HSI service are 0.18 Erl and 1/10, respectively. Internet group management protocol (IGMP) request message is used for user channel switching request and is a negligible quantity in offered traffic estimations.

### Table 2: Generated traffic per characteristic household.

<table>
<thead>
<tr>
<th>Service</th>
<th>Downlink traffic</th>
<th>Uplink traffic</th>
<th>Oversubscription</th>
<th>Total traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSI</td>
<td>1.012 kbit/s</td>
<td>256 kbit/s</td>
<td>1/10</td>
<td>126.8 kbit/s</td>
</tr>
<tr>
<td>IP telephony</td>
<td>115 kbit/s</td>
<td>115 kbit/s</td>
<td>0.18 Erl</td>
<td>41.4 kbit/s</td>
</tr>
<tr>
<td>IP TV</td>
<td>5.000 kbit/s</td>
<td>IGMP request</td>
<td>-</td>
<td>5.000 kbit/s</td>
</tr>
<tr>
<td>Sum</td>
<td>6.127 kbit/s</td>
<td>371 kbit/s</td>
<td>-</td>
<td>5.168,2 kbit/s</td>
</tr>
</tbody>
</table>

### 4. Optimization Results

Three different user demand scenarios are considered for the optimization calculations. In the first scenario, a “near future proof” 30 Mbit/s offered downlink speed for the majority of households is presumed, as shown in Table 3. It is presumed that an average household uses two IP TV services with an average bit rate 5 Mbit/s, one IP high definition TV (HDTV) service with an average bit rate 15 Mbit/s and two IP telephony services with an average bit rate 115 kbit/s. An average HSI service user profile has 5.060 kbit/s downlink speed and 2.024 kbit/s uplink speed. Oversubscription factors are considered, as shown in Table 2.

The driving factor for required local loop length estimation is 30,920 kbit/s peak downlink traffic. Considering the Fig. 4, the corresponding xDSL technologies are VDSL and VDSL2 with the “reach of xDSL technologies” input parameter (R), 400 m and 900 m, respectively.

In Scenario 2, a different HSI service user profile is presumed, as shown in Table 4. In this case, the driving factor for required local loop length estimation is 65,710 kbit/s peak downlink traffic. Considering the Fig. 4, the corresponding xDSL technology is VDSL2 with the “reach of xDSL technologies” input parameter (R), 200 m.

Scenario 3 considers FTTH solution, which is a future proof from the offered traffic point of view. In this case the “reach of xDSL technologies” input parameter (R) in the optimization algorithm is set to zero and “investment threshold” is set to one – the fiber has to be reachable from every household.

Scenario 2 has two sub-cases for different input parameters, R. To summarize, there are four scenarios, three with combined VDSL/VDSL2 and FTTN deployment and one with point-to-point FTTH solution.

### Table 3: Presumed maximal generated traffic per household, Scenario 1.

<table>
<thead>
<tr>
<th>Service</th>
<th>Downlink traffic</th>
<th>Uplink traffic</th>
<th>Oversubscription</th>
<th>Total traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSI</td>
<td>5.060 kbit/s</td>
<td>2.024 kbit/s</td>
<td>1/10</td>
<td>708.4 kbit/s</td>
</tr>
<tr>
<td>2 x IP telephony</td>
<td>230 kbit/s</td>
<td>230 kbit/s</td>
<td>0.18 Erl</td>
<td>82.8 kbit/s</td>
</tr>
<tr>
<td>2 x IP TV</td>
<td>10.000 kbit/s</td>
<td>IGMP request</td>
<td>-</td>
<td>10.000 kbit/s</td>
</tr>
<tr>
<td>1 x HDTV</td>
<td>15.000 kbit/s</td>
<td>IGMP request</td>
<td>-</td>
<td>15.000 kbit/s</td>
</tr>
<tr>
<td>Sum</td>
<td>30.920 kbit/s</td>
<td>2.254 kbit/s</td>
<td>-</td>
<td>25.791,2 kbit/s</td>
</tr>
</tbody>
</table>
3.1 Urban Copper Cable Access Network

The characteristic urban central office (CO) area consists of up to six major multi-pair copper cables, each with more than one thousand connected users. Each of these multi-pair cables represents a CAN, as shown in Fig. 2. The optimization planning for the residential urban CAN with 1.125 connected households (users) has been made. The belonging local cable network (LCN) is shown in Fig. 5. The circle with label CO represents the central office and black dots represent labelled joints in the LCN. A household density in the corresponding urban municipality is 298 households per square kilometer.

![Fig. 5 Characteristic urban LCN.](image)

Optimization scenario results are shown in Table 5. According to different scenario presumptions (1a, 1b, 2) the output parameters are the following: the number of required RDSLAMs, the average optical fiber dig length per household, the average number of households per RDSLAM and the average total traffic at the RDSLAM. The average total traffic at the RDSLAM is calculated considering generated traffic per characteristic household at the present time (Table 2). For all calculations with possible xDSL and FTTN combinations (Scenario 1a, 1b and 2) the input parameter, $N$, is 24 households (users). The input parameter, $N$, for the FTTH Scenario 3, is set to 1, because the fiber has to be reachable from every household. Also the output for Scenario 3 is slightly different – in the FTTH case, the RDSLAMs are not required, therefore only the average optical fiber dig length per household is calculated.

Proposed remote DSLAM installation places for Scenario 1a are presented as larger marked joints in LCN network, as shown in Fig. 6.

![Fig. 6 RDSLAM placement for urban Scenario 1a $(R = 900 \text{ m}, N = 24)$.](image)

Almost linear dependence between the reach of xDSL technologies, $R$, and the required RDSLAM number, is an interesting characteristic of urban CAN. If the $R$ is doubled, we can plan approximately three RDSLAMs less. The difference between an average optical fiber dig length in Scenario 2 and Scenario 3, and the average number of households per RDSLAM, are important parameters from the economic point of view. In the urban scenario, the average dig length jump per household is 7.4 m or 355 %, if migration from VDS2/FTTN solution to FTTH scenario is considered.

As an additional result of optimization, the dependence between the reach of xDSL technologies, $R$, and the average optical fiber dig length for different investment thresholds, $N$, can be presented, as shown in Fig. 7. The investment in optical access network deployment in urban areas, concerning the optical dig length, starts rapidly increasing when the investment threshold, $N$, is less than 48 households (users) and the reach of xDSL technologies, $R$, is shorter than 300 m.

### Table 4 Presumed maximal generated traffic per household, Scenario 2.

<table>
<thead>
<tr>
<th>Service</th>
<th>Downlink traffic</th>
<th>Uplink traffic</th>
<th>Oversubscription</th>
<th>Total traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSI</td>
<td>40.480 kbit/s</td>
<td>20.240 kbit/s</td>
<td>1/10</td>
<td>6.072.4 kbit/s</td>
</tr>
<tr>
<td>2 x IP telephony</td>
<td>230 kbit/s</td>
<td>230 kbit/s</td>
<td>0.18 Erl</td>
<td>82.8 kbit/s</td>
</tr>
<tr>
<td>2 x IP TV</td>
<td>10.000 kbit/s</td>
<td>IGMP request</td>
<td>-</td>
<td>10.000 kbit/s</td>
</tr>
<tr>
<td>1 x HDTV</td>
<td>15.000 kbit/s</td>
<td>IGMP request</td>
<td>-</td>
<td>15.000 kbit/s</td>
</tr>
<tr>
<td>Sum</td>
<td>65.710 kbit/s</td>
<td>20.470 kbit/s</td>
<td>-</td>
<td>31.155.2 kbit/s</td>
</tr>
</tbody>
</table>
Shortening the reach of xDSL technologies, $R$, the average calculated total traffic, according to statistical presumptions, decreases, as shown in Fig. 8. Dependence between the average total traffic at RDSLAM and the reach of xDSL technologies, $R$, for different investment thresholds, $N$, has almost linear characteristics. That is in accordance with almost linear dependence between reach of xDSL technologies, $R$, and the required RDSLAM number, $N$, as shown in Table 5 ($N = 24$).

In the next chapter similar analysis is made for characteristic rural network.

### 3.2 Rural Copper Cable Access Network

The characteristic rural central office (CO) area consists of up to three major multi-pair copper cables, each with less than five hundred connected users. Each of these multi-pair cables represents a CAN, as shown in Fig. 2. The optimization planning for the rural CAN with 338 connected households (users) has been made. The belonging local cable network (LCN) is shown in Fig. 9. The circle with label CO represents the central office and black dots represent labeled joints in the LCN. A household density in the corresponding rural municipality is 19 households per square kilometer.

Optimization scenario results are shown in Table 6. According to different scenario presumptions (1a, 1b, 2, 3) the output parameters are the same as in urban network case in the previous chapter. The first important difference between the urban and the rural network analysis is that in the rural case the investment threshold, $N$, of 24 households (users), excludes the influence of the reach of xDSL technologies on the optimization result. In other words, the RDSLAM is always planned for 33.8 households on average. In this case, many households are not served with corresponding scenario broadband services. The investment threshold, $N$, is therefore lowered to 6 households (users), as shown in Table 7.

The dependence between the reach of xDSL technologies, $R$, and the required RDSLAM number, has an almost linear characteristic – as in the urban CAN network. If the $R$ is doubled, we can plan approximately six RDSLAMs less. In the rural case, the average dig length jump per household is 31.2 m or 42%, if migration from VDSL2/FTTN solution to FTTH scenario is considered.

The dependence between the reach of xDSL technologies, $R$, and the average optical fiber dig length for different investment thresholds, $N$, is presented in Fig. 10. The investment in optical access network deployment in rural areas, concerning the optical dig length, starts rapidly increasing when the investment threshold, $N$, is less than 12 households (users) and the reach of xDSL technologies, $R$, is shorter than 300 m.
Fig. 10 Dependence between the average optical dig length per household and the reach of xDSL technologies \( R \) for different investment thresholds \( N \).

Shortening the reach of xDSL technologies, \( R \), the average calculated total traffic, according to statistical presumptions, decreases, as shown in Fig. 11. Dependence between the average total traffic at RDSLAM and the reach of xDSL technologies, \( R \), for different investment thresholds, \( N \), has almost linear characteristics. That is in accordance with almost linear dependence between the reach of xDSL technologies, \( R \), and the required RDSLAM number, \( N \), as shown in Table 7 (\( N = 6 \)). It can be noticed that the optimization calculation limits constant value, as shown in Table 6. The average total traffic at RDSLAM and the reach of xDSL technologies, \( R \), for investment thresholds, \( N \), higher than 18 households (users), become independent.

Fig. 11 Dependence between the average total traffic at remote DSLAM and the reach of xDSL technologies \( R \) for different in investment thresholds \( N \).

If the average considered broadband services (Table 2) are made available to all households (users), the next important issue to be considered is in rural CAN. For average services offered, as shown in Table 2, the 6.127 kbit/s peak download speed is required. That can be offered through local loops, shorter than 3 km, as shown in Fig. 4. Proposed RDSLAM installation places for scenarios offering average services are shown in Fig. 12, where the investment threshold, \( N \), is set to 24, as in the urban case.

Fig. 12 RDSLAM placement for rural scenario offering average services (\( R = 3.000 \text{ m}, N = 24 \)).

For offering average services through rural CAN, three RDSLAMs are required. In this case the average optical fiber dig length is 22.2 m, the average number of households per RDSLAM is 90.7 and the average total traffic at RDSLAM is 11.7 Mbit/s.

5. Conclusion

Optimization of two presented characteristic broadband access network planning has shown some important results and gives us several techno-economical clues for effective broadband deployment in underserved rural areas. Understanding of difference between rural and urban scenarios is a key issue for bridging the geographical digital divide.

It has been shown that CAPEX of the rural study with FTTH scenario is approximately ten-times higher than CAPEX of the urban study with FTTH scenario, when offering average estimated services and the optical fiber dig length is applied. Urban and rural networks are similar in terms of dependence between the reach of xDSL technologies parameter and average total traffic estimation at RDSLAM if the investment threshold is set below certain value – for urban and rural scenario, \( N = 96 \) and \( N = 12 \), respectively. In the urban scenario with FTTH solution and \( N = 24 \), the average dig length per household is approximately five-times lower than average dig length per household in the rural scenario with FTTH solution and \( N = 6 \). The CAPEX for VDSL(2)/FTTN rural deployments are from twenty five to thirty-times higher than the CAPEX for the same urban deployments if the optical fiber dig length is applied. If the average presumed services have to be delivered to the majority of households, the investment threshold has to be four-times lower for the rural scenario than the urban one. The cost of
RDSLAM installation is therefore much higher in rural scenarios and the average total traffic at RDSLAM is ten to twenty-times lower than in urban ones. Low population density areas are therefore appropriate for wireless technology deployments (e.g., WiMAX).

Further research work will involve method improvement for fixed broadband wireless systems planning and implementation of techno-economical parameters in output parameters (e.g., internal rate of return, net present value). Input parameters will be extended using infrastructure costs for economic evaluations. One of the important future studies is statistical comparison of different copper access networks from various operators with focus on optimal technology selection for bridging geographical digital divide in sparsely populated areas.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>R</th>
<th>N</th>
<th># of remote DSLAMs</th>
<th>Average optical fiber dig length per household</th>
<th>Average # of households per remote DSLAM</th>
<th>Average total traffic at remote DSLAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>900 m</td>
<td>24</td>
<td>3</td>
<td>1.8 m</td>
<td>372.3</td>
<td>48,1 Mbit/s</td>
</tr>
<tr>
<td>1b</td>
<td>400 m</td>
<td>24</td>
<td>6</td>
<td>2.0 m</td>
<td>186.2</td>
<td>24,1 Mbit/s</td>
</tr>
<tr>
<td>2</td>
<td>200 m</td>
<td>24</td>
<td>9</td>
<td>2.9 m</td>
<td>123.0</td>
<td>15.9 Mbit/s</td>
</tr>
<tr>
<td>3</td>
<td>FTTH</td>
<td>1</td>
<td>FTTH</td>
<td>10.3 m</td>
<td>FTTH</td>
<td>FTTH</td>
</tr>
</tbody>
</table>

Table 6 Optimization results for rural scenarios (N = 24).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>R</th>
<th>N</th>
<th># of remote DSLAMs</th>
<th>Average optical fiber dig length per household</th>
<th>Average # of households per remote DSLAM</th>
<th>Average total traffic at remote DSLAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>900 m</td>
<td>24</td>
<td>10</td>
<td>30.7 m</td>
<td>33.8</td>
<td>4.4 Mbit/s</td>
</tr>
<tr>
<td>1b</td>
<td>400 m</td>
<td>24</td>
<td>10</td>
<td>36.7 m</td>
<td>33.8</td>
<td>4.4 Mbit/s</td>
</tr>
<tr>
<td>2</td>
<td>200 m</td>
<td>24</td>
<td>10</td>
<td>36.7 m</td>
<td>33.8</td>
<td>4.4 Mbit/s</td>
</tr>
<tr>
<td>3</td>
<td>FTTH</td>
<td>1</td>
<td>FTTH</td>
<td>105.7 m</td>
<td>FTTH</td>
<td>FTTH</td>
</tr>
</tbody>
</table>

Table 7 Optimization results for rural scenarios (N = 6).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>R</th>
<th>N</th>
<th># of remote DSLAMs</th>
<th>Average optical fiber dig length per household</th>
<th>Average # of households per remote DSLAM</th>
<th>Average total traffic at remote DSLAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>900 m</td>
<td>6</td>
<td>17</td>
<td>48.4 m</td>
<td>19.8</td>
<td>2.5 Mbit/s</td>
</tr>
<tr>
<td>1b</td>
<td>400 m</td>
<td>6</td>
<td>24</td>
<td>58.9 m</td>
<td>14.1</td>
<td>1.8 Mbit/s</td>
</tr>
<tr>
<td>2</td>
<td>200 m</td>
<td>6</td>
<td>30</td>
<td>74.5 m</td>
<td>11.3</td>
<td>1.5 Mbit/s</td>
</tr>
<tr>
<td>3</td>
<td>FTTH</td>
<td>1</td>
<td>FTTH</td>
<td>105.7 m</td>
<td>FTTH</td>
<td>FTTH</td>
</tr>
</tbody>
</table>

Acknowledgments

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References

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