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B a l k a n i c a

New Series Vol.23, 2009, Fasc. 3-4

Algorithms for Designing Optimized Fixed Broadband Networks [1]

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This paper presents the use of graph theory for designing fixed broadband networks with optimized link routes among transmission nodes. The cost function is the total length of links and the number of households covered by a two-layer transmission network. The topology of a backbone network is a ring and the topology of a distribution network is a tree. For designing the backbone network the "travelling salesman problem" is solved. The distribution network is optimized using Prims algorithm for the minimum spanning tree. Other solutions, i.e., the dynamic programming, allow to designate other architecture elements of the networks, as well as to obtain a better efficiency of optimization process of the graphs.

1. Introduction

The process of network design is very challenging for telecom operators, especially for those that operate in the green field. The obvious constraints that have to be taken into account include availability of financial resources and time to launch of services. Moreover, operators have to consider the geographical coverage of the network, population density and demand, as well as the transmission capacity of the whole network. To achieve a trade-off between these, often contradictory, objectives they have to carefully plan the overall length of the transmission network and the number of households that will become consumers of different Internet services like access to Internet, Web TV, Voice over IP, etc.

[1] This work is done within the "Broadband Network for Eastern Poland" project co-financed from EU funds within the Operational Program Development of Eastern Poland 2007-2013

In this paper we present algorithms based on the graph theory that can be used to design a fixed broadband network. Network optimization takes into account the total length of links and the number of households covered by the network as two key variables of the cost function.

The design process presented in the paper concerns a network architecture that is composed of two layers: backbone and distribution. A topology of the former is a ring that connects main cities in a province. The latter layer is designed in the topology of a tree that links cities and villages ranked according to their size expressed in the number of households.

Algorithms used for optimization are chosen separately for each layer. For the backbone network the "traveling salesman problem" is solved, and for the distribution network Prims algorithm is used to find a minimum spanning tree. The variables being optimized are the number of backbone and termination nodes as well as the total length of both networks. Other presented algorithms allow determining the remaining elements of the network architecture.

The paper is organized as follows: general assumptions and constraints for network planning are listed in Section 2. Section 3 presents guidelines for designing and dimensioning fixed broadband networks. In Section 4 we describe algorithms that compute locations of the backbone nodes and the actual location of the backbone network links. An algorithm for determining locations of termination nodes and of links of the distribution network is discussed in Section 5. Additional scenario analysis is described in Section 6.

2. Design assumptions for network model

2.1. Logical architecture

The starting point for selection of a technical model for Wide Area Network (WAN) planning is to determine an architecture of the logical network. In this regard, it is recommended to use a hierarchical network composed of two layers:

* backbone network,
* distribution network

This, in contrast to a one-layer network, allows for functional division of the layers depending on the tasks they perform throughout the network.

The backbone network consists of:

* passive components – premises for backbone nodes, together with the necessary infrastructure to ensure secure and reliable functioning of active

components; cable pipes and cable ducting system; optical fiber cables; passive accessories for fiber optics;

* active components – active devices of the backbone network.

The backbone network layer performs the following functions:

* transmission of traffic in the backbone network,
* aggregation of traffic from distribution networks.

The distribution network layer consists of:

* passive components – facilities for distribution nodes, together with infrastructure necessary to ensure secure and reliable functioning of active components in the distribution network; cable pipes and cable ducting system; optical fiber cables; passive accessories for fiber optics;
* active components – active devices of the distribution network.

The distribution network layer performs such functions as:

* transmission of traffic between last mile networks and the backbone network,
* aggregation of traffic from last mile networks.

Hierarchical approach is crucial for a future operator of the network infrastructure, because it significantly simplifies traffic management in the network, reduces the time needed to determine failures and the range of an outage (thus decreasing costs of supervision, monitoring and maintenance of the whole transmission system).

2.2. Network topology

In the design process it is necessary to make a proposal of the most efficient topology for each layer, taking into account their roles in the network. For the backbone network a ring topology is recommended. This solution is a trade-off between CAPEX and reliability.

Analyzing this solution in terms of performance and reliability of the backbone network, we come to the conclusion that the cost of building of the network in the ring topology is much lower than that in the mesh topology. This is due to the lack of necessity to make multiple cross-connections between nodes. Another saving is due to fewer optical interfaces used in transmission devices of the backbone network.

The ring provides a high level of reliability. Even when the transmission medium is broken at any point or a failure of node occurs, it allows for uninterrupted operation of the network. Damage to the transmission medium does not cause breakdown of the whole network, and only the ring is converted by the bus topology. A failure of the node results in unavailability of only the lower layer of the distribution network connected to this node.

One problem in building a network in the ring topology is smaller ability to manage traffic in comparison to the mesh topology. Traffic between nodes which are not direct neighbours must be routed through intermediate nodes. In case of the mesh topology there exists a possibility of direct routing of the traffic between all nodes. However, taking into account the current state of development of transmission technologies, it can be concluded that this limitation is negligible. Optimization of network traffic can be achieved through configuration of the transport layer in which virtual cross-connections using Dense Wavelength Division Multiplexing (DWDM) optical channels may be set up. In this way, the network that has the physical ring topology can be logically configured to have the mesh topology.

Another way to reduce that limitation and additionally to increase the reliability of the network is to build one or several cross-connections which will divide a single ring into two or more smaller ones. Such modification should be determined on the basis of demographic and geographic factors, cost, expected traffic volume and operators strategies in terms of network development and level of its reliability.

For the distribution layer the tree topology is recommended. The tree topology is less expensive to build, compared with e.g. a star or ring topology. Savings are due to the possibility of optimization of link relations and minimizing the number of duplicate links.

The network built in the tree topology, together with modern traffic aggregation facilities, allows optimization of network links and enables easy management of traffic. Another advantage is its easy scalability and the ability to easily add new nodes by means of a connection with one of the existing nodes at any level of the tree. In addition, there is also a possibility to set up cross-connections between branches, which makes it possible to create any network topologies in the distribution network.

2.3. Transmission medium

As a medium for the transmission network a single-mode optical fibre is recommended. It is characterized by the best technical parameters, allowing to obtain the best transmission parameters. It allows using xWDM techniques as well as ones without this multiplexing.

2.4. Transmission technologies

In the backbone network it is recommended to deploy transmission based on WDM. WDM is a multi-service transmission platform of great capacity enabling the transmission of any signals over long distances. It allows simultaneous and independent transmission of many optical signals with different wavelengths (optical channels) in one optical fibre. With protection mechanisms implemented, it is possible to build a versatile and reliable transmission network of large throughput.

In the distribution network it is not planned to use WDM technology. Throughput offered by the WDM system far exceeds users demand for transmission bandwidth. The use of this technology would bring down the cost-effectiveness of the project. WDM is considered as a bearing technology, and not as a service technology, so the possibility of using WDM technology in the distribution network may be considered by the operator of infrastructure on a case by case basis – for example in such cases like: lack of available fibres, insufficient throughput, etc.

2.5. Transmission protocol

As the network transmission protocol Multi-Protocol Label Switching (MPLS) is strongly recommended. It allows to achieve the highest quality transmission parameters, and ensures flexible and efficient management of transmission network by defining different quality levels and classes of services.

3. Guidelines for designing and dimensioning fixed broadband networks

3.1. General introduction

Administrative division in Poland distinguishes provinces, districts and communes. In this project we take mainly a province and its districts into account. The design assumptions are following:

1. transmission network is built for a carriers carrier operator that is not allowed to own last mile networks;

2. subscribers in communes are served by last mile operators;

3. last mile operators can build wireline/wireless last mile networks or acquire them from the incumbent operator using e.g. Wholesale Line Rental or Unbundling Local Loop services.

3.2. General assumptions for dimensioning

The following assumptions describe the logical and physical architecture of designed networks:

* broadband network for a province is composed of two layers: a backbone network and a distribution network (Fig. 1); the architecture does not include access layer (last mile networks);

* considering the logical architecture, backbone nodes and links between them form a backbone network. These nodes operate as both transit east-west ones as well as distribution ones for distribution networks related to these nodes;

* selected nodes in the backbone network shell also carry out the functions of Points of Interconnection (PoI) with networks of other operators;

* the distribution networks are the networks with termination nodes that perform a function of Points of Access (PoA) to the whole WAN;

* in distribution nodes it is possible to connect last-mile networks of operators who deliver services to end users, or to build links to other nearby existing PoA located in other places; these links form then next parts of the distribution network;

* the backbone network is built in the ring topology, or few rings connected one with another;

* the distribution network is built in the tree topology;

* considering the physical layer, both nodes of the backbone network and termination nodes of the distribution networks are in specific locations that are equivalent with existing inhabited places (cities and villages) in the area of a given province;

* WAN is designed in a uniform (with few exceptions only) optical technology;

* network links are dimensioned along public roads;

* from the perspective of optimization, both network layers (backbone and distribution) are regarded as strongly connected and undirected weighted graphs; vertices of the graph correspond to nodes in both backbone and distribution networks; weights relate to edges in the graph and mainly

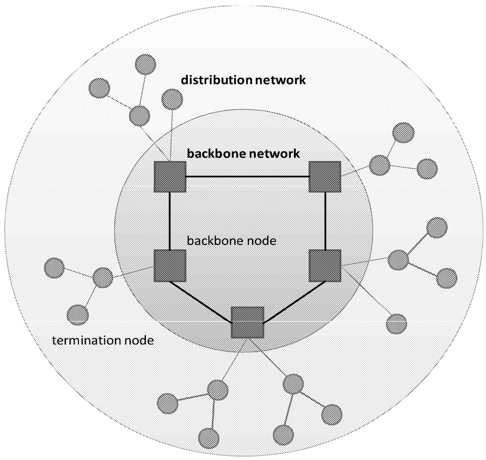

Figure 1: The proposed scheme of network architecture for a province

reflect the road distances between the vertices of the graph; minimization of the cost of building of the network relates the minimization of the road distance between the nodes in the backbone network and ones in the distribution networks.

In the case of designing a network for a province one ought to specify:

* a number of nodes;
* a number of rings and a number of links between the rings;
* locations of nodes;
* allocation of nodes to the rings;
* branches of the rings that constitute the distribution networks.

A concept of network dimensioning is visualized in (Fig. 2).

The number of nodes in the backbone network determines a number of associated distribution networks. This gives a possibility to scale the architecture across the network depending on the traffic which users of broadband services generate. A small number of nodes reduces the cost of building, but at the same time influences the size of distribution networks and thus significantly increases traffic routed from distribution networks to the backbone network. A large number of nodes results in inefficient use of these nodes for purposes of the distribution infrastructure and in an increased cost of building the backbone network.

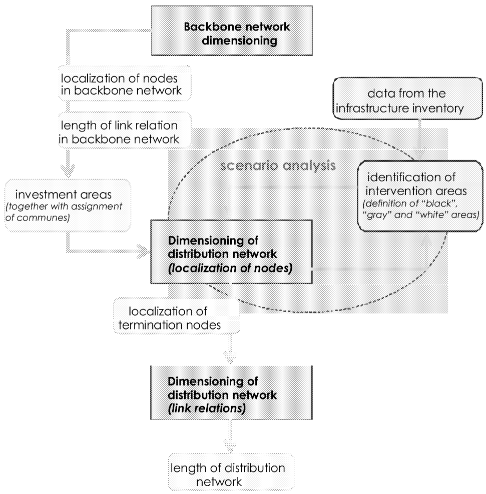

Figure 2: Visualization of network dimensioning process

From the point of view of designing broadband networks, the best approach seems to be building the backbone network on a basis of several nodes (the maximal number of nodes should not exceed the number of districts in a province). In the Polish conditions it can be assumed that one distribution node is built for the area covering from 100,000 to 200,000 residents (from 30,000 to 70,000 households), taking into account the degree of population density in the area.

The analysis of capacity of different distribution nodes is presented in Table I.

For reliability reasons the backbone network is designed in the topology of two rings (composed of a single ring and an additional cross-connection between its selected nodes). Expansion of the backbone network should be preceded by an analysis of: events and traffic in the network during its operation; forecasts of further development of the associated distribution- and last mile- networks, as well as forecasts of development of services provided to customers.

Nodes of the backbone network will be located in selected cities being the seat of district authorities, so that setting of points of interconnection with networks of other operators is possible (typically PoIs are located in those places). Due to association of distribution nodes with distribution networks, a distribution node will be located only in a district which belongs entirely to a distribution area. The distribution area comprises typically several districts that may be also split among few neighbouring distribution areas due to the optimizing process.

In specific cases (geography, availability of road connections, and requirements for reliability) it is possible to locate distribution nodes outside the ring. Such remote distribution node is then connected with the nearest backbone node in the ring.

In order to design distribution networks within the province one should identify:

* a number of distribution areas (a number of distribution networks);
* locations of termination nodes (PoA) in distribution networks;
* locations of distribution nodes;
* assignment of termination nodes to distribution networks.

The number of distribution areas is directly related to the number of backbone nodes planned. Distribution areas will include a single district or several neighbouring districts. Joining of districts in one distribution area is performed on the basis of expert assessment, taking into account the overall population of joint districts, their mutual proximity and location of districts in the province.

Termination nodes within the distribution network will be implemented at the commune level in the following locations:

* seats of commune authorities;
* places with a number of households exceeding an assumed threshold value;
* places where schools are located.

The threshold number of households will be chosen experimentally, separately for different distribution areas on the basis of histograms of population in each place.

It is assumed that in a commune there are at least three termination nodes of the distribution network, regardless of meeting the conditions defined above. In this approach, locations of termination nodes will be identified, taking into account the criterion of maximum number of households in the analyzed places as well as their geographical position in the commune. In each of the above pre-defined cases, localizations of termination nodes in the distribution networks will be identified taking into consideration the possible range of last mile networks built on the basis of these nodes. This geographical range comprises areas where a service of broadband access to Internet has not yet been offered (i.e. so-called "white" areas), or areas in which such service is offered but only with a network infrastructure of a single operator (”grey” areas). The third type of investment areas is called ”black”. They denote areas where there are at least two operators owing separate transmission infrastructures.

The approach to situate the termination nodes in the distribution networks allows building PoAs and last mile networks associated with them on the areas suffering from digital divide, and also expanding the range of these distribution networks to remote areas where last mile operators have already developed their networks.

Localization of backbone nodes is determined by the choice of locations that enable to minimize the length of the ring that connects them. In case of distribution areas corresponding to the area of a single district, the location of a backbone node is evident in the capital of the district. In case of distribution areas composed of two or three districts, the location of the backbone node is associated with one of the capitals of these districts and it is required to run a procedure of searching minimum path through the ring for different possible locations of backbone nodes. For a given set of locations of backbone nodes one computes an optimal path for the ring, and then compares its length with the lengths of the paths for the rings obtained for other combinations of the backbone nodes.

A single distribution network includes a set of locations selected as termination nodes (PoA) belonging to communes that are nearest to a given distribution node. Qualification ”commune that is the nearest to the given distribution node” means a commune for which a distance (calculated as the distance along public roads) between the seat of the commune and the distribution node is minimal. In this way we define a distribution area of which the smallest element is a commune and which does not agree necessarily with the administrative boundaries.

3.2. Examples of architecture deployment

Example of a provincial backbone network is presented in (Fig. 3). For this case a backbone network has a topology with a single ring and 13 backbone nodes. Each backbone node is both a point of interconnection and a distribution node. The range of the distribution network includes area of one or two districts; however, as stated earlier in the assumptions, the coverage of the distribution network does not have to coincide with administrative boundaries of districts.

Example of a distribution network is shown in (Fig. 4). As it is shown, the range of a distribution network for which there is a distribution node in the capital of the district may cover an area extending beyond the administrative boundaries of the district.

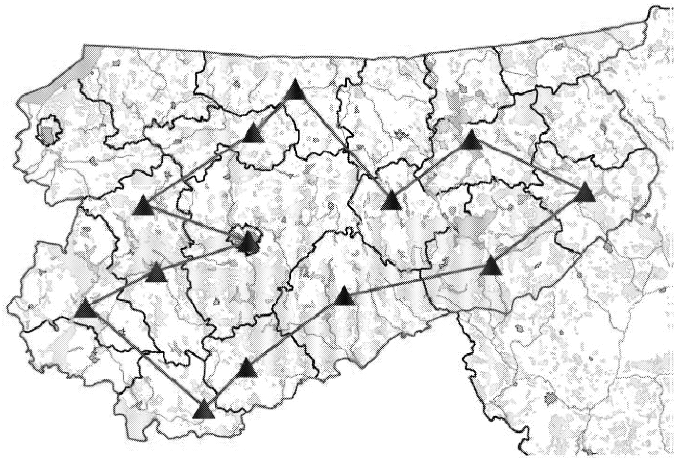

Figure 3: Example of backbone network within a province

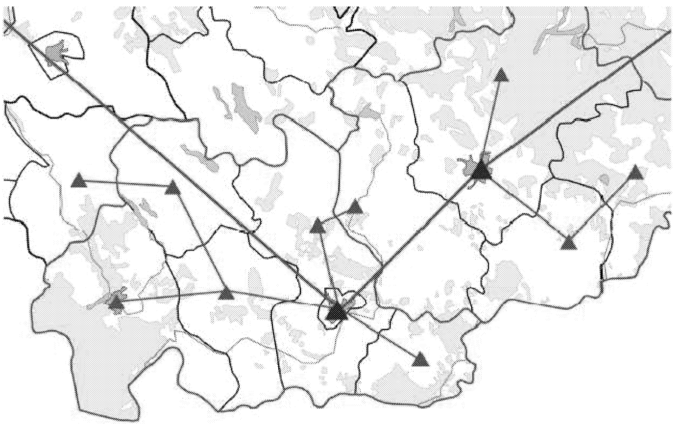

Figure 4: An example of a distribution network

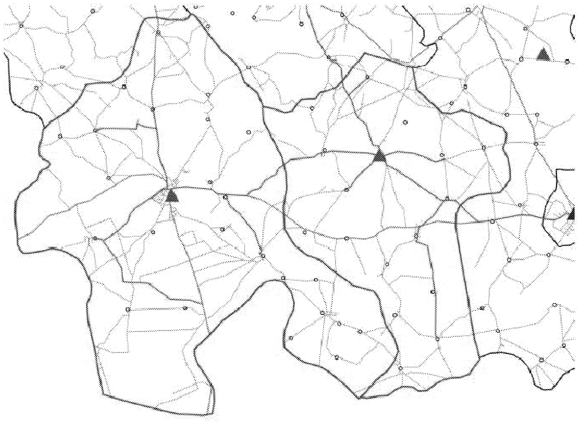

Figure 5: Example of network link routes across districts

The process of assigning each location to the distribution node in a district shall be done on the commune level. For each commune there shall be determined a distribution node (on the district level) for which a distance from a given location is the smallest. In this way, clusters of communes are created. As a result, these clusters encompass the areas located in a range of a given distribution node. These areas constitute an investment area on which the distribution network is built, and network operators may connect their last mile networks to the transmission network. It is assumed that links of the distribution network as well as ones of the backbone network will be built along roads (Fig. 5).

A distribution network which has the topology of a tree will be optimized taking into account the total length of links between termination nodes. A fork of the network infrastructure (i.e. division of a fibre cable into parts of a less number of optical fibres) may take place both at the planned nodes of the distribution network, and at cross-roads.

Termination nodes in the distribution network allow last mile operators to access to whole regional network in the province. This connection may be implemented on the basis of one of the two scenarios presented beneath.

The first scenario (Fig. 6) assumes a direct connection of a last mile network to the distribution network. In this case, an access node of the last mile operator overlaps with PoA of the distribution network, and the last mile network is built around this termination node. Collocation facilities at the termination node may be used by the last mile operator.

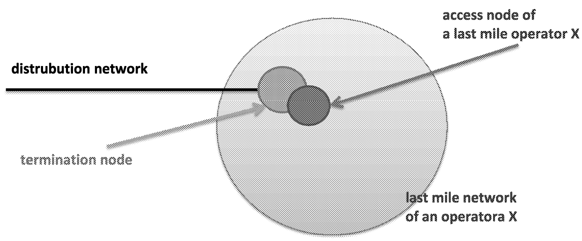

Figure 6: Scenario with direct connection of last mile operator to the distribution network

The second scenario (Fig. 7) relates to a situation in which a last mile operator builds its own piece of the transmission network and at its access end it installs an access node. This is the case when the termination node of the distribution network is in a different location than the one chosen by the last mile operator plans to build their access network. A transmission link between the distribution network and the last mile network is in PoA of the former. The auxiliary transmission network can be built in any technology which is not limited to solutions already applied in other parts of the network.

4. Algorithms for determining locations of nodes and of link routes of the backbone network

4.1. Algorithm to determine the location of a backbone node

This algorithm may be described by the following steps:

1. Determining the optimal number of nodes, K, in the backbone network in a province

On the basis of a number of residents in a province and assumptions taken above (i.e., a distribution node serves the area inhabited by 100,000 to 200,000 residents; the number of nodes should not exceed the number of districts in a province), the calculation of the optimal number of nodes in the backbone network in the province is performed.

Input data are:

* a number of district cities in the province;

* a number of households in the province split by communes.

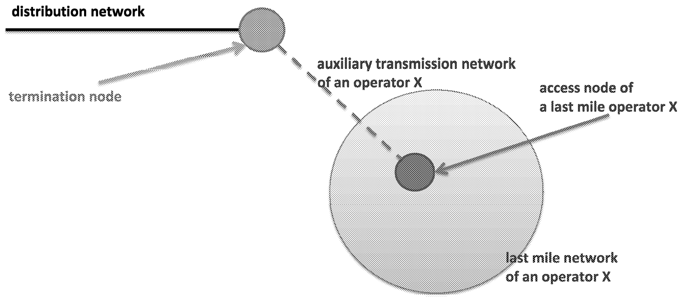

Figure 7: Scenario of connection of a last mile network to the distribution network with an additional transmission link

2. Determining a list of potential locations of nodes, N, in the backbone network

As potential locations of backbone nodes all districts cities are taken. In case of a municipal district and a district surrounding it, the building of one backbone node is assumed.

Input data are:

* a list of district cities in the province.

3. Determining a cluster

Around backbone nodes the clusters of communes assigned to a distribution node connected to a given backbone node are defined.

Input data are:

* a list of communes in a province;
* a table of distances between all district cities (potential locations of backbone nodes) and commune places;
* a number of households in all communes.

An algorithm for selecting locations of backbone nodes and for defining clusters works as follows assuming that:

N – a number of possible locations of backbone nodes in a province (equal to a number of district cities in the province);

K – the optimal number of backbone nodes in the province;

L_i – a symbol of i-th city being a location of the backbone node in the province (where i varies from 1 to K);

CL_i – a K element subset of a set of N potential locations of backbone nodes (where i is an index of a specific combination and it varies from 1 to $\binom{N}{K}$;

a) determining all possible combinations $CL_i = \{L_1, ..., L_K\}$;

b) clusters are built around a given backbone node by clustering communes for which the road distance between the seat of the commune and the location of the backbone node is the smallest (i.e., a cluster comprises all communes for which the given backbone node is the nearest among all backbone nodes analyzed in a given case);

c) for each cluster it is determined the total length (d_j) of paths between the seats of communes and the node L_j; and also the number of households (G_j) on the area of the cluster;

d) for each subset CL_i the standard deviation of the number of households is calculated;

e) each variant CL_i with locations of K backbone nodes is described by: (i) a sum of lengths of paths connecting the seats of commune authorities with the backbone nodes in each cluster $D_i = d_1 + d_2 + ... + d_K$, and ($ii$) a value of standard deviation of the number of households (SG_i);

f) selecting a subset CL_i with locations of the backbone nodes is made using a weighted sum (W) that reflects a degree to which the design objectives are met; the value of the coefficient W is calculated on the basis of the following formula:

$$W = \alpha(\frac{L_{min}}{L_i}) + (1-\alpha)(\frac{SG_{min}}{SG_i}) \to max, \tag{0.1}$$

for $i = 1, , K$, where α is a weight; the assumption is $\alpha = 0.95$.

4. Expert review of results

The aim of the expert review of the obtained results is to adjust the clustering process prepared by the algorithm. An adjustment may include among other things the change of the assignment of an inhabited place or commune to a given cluster, e.g. for inhabited places located on the boundary of clusters.

4.2. Algorithm to determine link routes in the backbone network

Input data for the algorithm that determines routes in the backbone network are following:

* locations of nodes of the backbone network in the province; they are specified by the previous algorithm (Section 4.1);

* existing road connections between locations of backbone nodes.

To determine the optimal (shortest) route of a link between backbone nodes one ought to solve the so-called "travelling salesman problem"[2] [5][6] for a given set of locations. To enable efficient execution of calculations for data including 15 25 backbone nodes, techniques of the dynamic programming (written in C language) are used that let reduce a computational complexity of the algorithm (for example, for 20 locations the run-time of the brute-force algorithm would be hundreds years, while the implementation based on the dynamic programming to solve the same problem needs several minutes).

The distance between locations of backbone nodes are specified on the basis of digital maps that describe roads in a province using ArcGIS software [2]. Such approach allows visualizing the routes of links later, taking into account the actual state of roads in the region.

5. Algorithms for determining locations of termination nodes and link routes of the distribution network

As input data to the process of dimensioning of the distribution network the following assumptions are taken:

* the number of backbone nodes and their locations;

* a list of all inhabited places (down to village administrators level), districts and communes in the province; it is needed to identify locations for potential termination nodes;

* clusters with communes that are assigned to them;

* road distances between all inhabited places within a cluster;

* the number of households in the inhabited places; it is needed to determine optimal locations for termination nodes.

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[2]The traveling salesman problem is an issue of the theory of graphs, which is to find a minimum Hamilton cycle in a complete weighted graph.

5.1. Algorithm for determining localization of termination nodes in the distribution network

A distribution network branch is determined individually for each cluster. Termination nodes are located primarily in commune cities in a cluster of the distribution network.

For each place which is the seat of a commune other inhabited places are assigned (to form together a group) so that the following conditions are jointly met:

* a distance (defined as a minimum distance calculated along the roads) between a given inhabited place and the seat of a commune is x km at most (a range of this distance used in the algorithm is 2 6 km);
* minimum number of households within the group is y (the assumed value is 70).

In the analysis, all places in the commune are considered; however they are first ranked according to their size (expressed in the number of households). An inhabited place already allocated to a group is excluded from further analysis.

Once all groups of inhabited places in the commune are specified, the algorithm allows to exclude from further analysis the places identified as "black" or "grey" as well as according to any other conditions if needed (it is an expert analysis of the obtained results).

A next step is to form groups for inhabited places where schools are situated. The process to form these groups of inhabited places is the same as for the seats of the communes.

In a next step groups for remaining places in the commune are formed in the same process as for the seats of the communes. The algorithm of determining groups for subsequent inhabited places proceeds according the size of these places (expressed in the number of households). Only places that were not assigned earlier to other groups are considered.

After these steps of the algorithm, there is an expert assessment of results. Inhabited places that do not belong to any groups, are assigned to one of existing groups on the basis of the estimated demand for services, geographical position, distance, etc.

When all locations of termination nodes are defined, a link route of the distribution network is determined using the following algorithm which determines an optimal route of the distribution network.

Assumed threshold value of the distance range of the group around a termination node has been estimated on the basis of technical parameters of last mile technologies which can be used to build the last mile networks. As representatives of these technologies both ADSL[3] (as an example of the technology based on a copper local loop) and WiMAX[4] (an example solution for a radio access link) were adopted.

For ADSL or ADSL2, in accordance with the parameters defined by ITU T standards (G992.1 and G992.5), broadband access is possible for the local loop length not greater than 3 4 km. But for the WiMAX radio technology (IEEE 802.16 standard) the distances range between ca. 5 and 7 km in conditions of non-line-of-sight (non-LOS) between a base station and a terminal (it is a typical situation for the last mile network).

5.2. Algorithm of determining the optimal distribution network

In case of the algorithm for determining the optimal distribution network the following set of information is collected:

* locations of the backbone nodes in a province;
* locations of the termination nodes in a province;
* existing road connections between backbone nodes and termination nodes.

To determine the optimal route of links between the distribution node and termination nodes one has to solve the problem of the minimum spanning tree (MST) for a graph in which vertices are nodes of the backbone and termination networks and edges are the distances between these nodes calculated along roads. To determine the minimum spanning tree, Prims algorithm was used (see appendix) [3][4]. For dense graphs (the distribution network is such a graph) Prims algorithm is characterized by less computational complexity than an alternative Kruskals algorithm.

Starting conditions of the algorithm are slightly modified so as to avoid having to modify data about road connections between nodes. In the classical implementation Prims algorithm is initialized with an empty list of selected connections for the minimum tree, and with a freely selected node of the graph. In the described case, the initial vertex of the graph corresponds to the location of the backbone node for a given distribution network.

The distance between the locations of backbone and termination nodes is calculated using ArcGIS software on the basis of the available digital maps that describe roads in the province. Such approach allows later visualizing the route of links, taking into account the actual state of the roads in the region.

[3]Asymmetric Digital Subscriber Loop
[4]Worldwide Interoperability for Microwave Access

The process of generating information about the distances between the selected locations of inhabited places is following:

* there are two tables (A and B) containing data about the places between which road distances have to be calculated;

* for each pair (ai, bj), where i is an index in table A, and j is the index in table B, the shortest path is calculated using the Network

Analyst tool that is a plug-in for ArcGIS application; information about the path, in addition to its length, contains also a set of segments of the roads, along which the path goes (it allows to visualize the path on a digital map).

Routes between nodes will be also dimensioned in order to determine the number of pairs of optical fibres that must be installed in pipes to offer required capacity for the distribution network. To optimize costs of optical fibres, a remote distribution node can be created. It is not situated together with the backbone node. In a link between a remote distribution node and a backbone node, the traffic aggregation technology can be implemented to reduce the overall costs of transmission infrastructure.

6. Designing scenarios

6.1. Number of rings in the backbone network

An increased number of rings in the backbone network layer assures the increase of efficiency and availability. It should be noted that the achievement of these results should be at acceptable cost. A greater number of cross-connections leads to the migration of the network topology from the ring to the mesh. One of the drawbacks of the latter technology is the unequal use of individual connections, and as a result – a lack of economic efficiency and complicated traffic management.

Therefore, in the backbone network one cross-connection will be set up. As common nodes of both rings formed by the cross-connection, one should use nodes which are located relatively close to each other (in order to minimize the costs of building an additional link) and which can generate the most traffic (since for them it is important to ensure high availability).

Further optimization of traffic in the backbone network should be implemented using DWDM mechanisms by creating virtual cross-connections based on optical channels.

6.2. Points of Interconnection

For each provincial network it is recommended to implement two Internet eXchange Points (IXP) with at least two Internet providers. In comparison to a single IXP, this solution enables to:

* obtain redundancy in access to the Internet;
* achieve independence of Internet provision;
* have opportunity to negotiate peering fees in a function of traffic volume;
* re-route traffic between IXPs in case of failure or upgrade of the node;
* gain many advantages in the field of traffic engineering and management.

In order to exchange traffic between WANs in neighbouring provinces, it is planned to build inter-province IXPs. The advantages of it are the following:

* reduction of traffic volumes in commercial IXPs where peering with Internet providers is done;
* decrease of peering costs because traffic is not transferred via commercial IXPs;
* greater opportunities for traffic engineering;
* additional protection of access to the Internet in the case of failure of IXP.

6.3. Scenario analysis

Scenario analysis of building the distribution network is based on a different density of termination nodes which settle a size of area where services within a local loop may be delivered. Four scenarios were defined: 2, 4, 5 and 6 km service area range of a termination node. The density of termination nodes differs each scenario from others. The greater density the smaller area is allocated to a given termination node and simultaneously the greater investments are needed. The area served by a termination node determines the length of a local loop to be built by an operator of the access network in order to offer services of the required quality. The number of nodes for each scenario is shown in Table 2. In all scenarios it is assumed that they cover 90% of population in the province.

We present the use of graph algorithms for designing optimized fixed broadband networks. A ring of the backbone network is optimized solving the

Table 1: THE NUMBER OF NODES FOR SCENARIOS

Scenario	2 km	4 km	5 km	6 km
Backbone	Distribution			
10	852	467	255	198

Table 2: THE ANALYSIS OF CAPACITY OF DIFFERENT DISTRIBUTION NODES [NUMBER OF HOUSEHOLDS]

Overbook coeff.	**Capacity**	**Average throughput per household**		
		1 Mbps	**2,25 Mbps**	**6 Mbps**
1	50 x 1 Gbps	100,0	44,000	16,700
	70 x 1 Gbps	140,00	62,200	23,300
	100 x 1 Gbps	200,000	88,900	33,300
2	50 x 1 Gbps	200,0	88,900	33,300
	70 x 1 Gbps	280,00	124,200	46,700
	100 x 1 Gbps	400,000	198,800	66,700

"travelling salesman problem," and a tree of the distribution network is computed by Prims algorithm. Both algorithms show their efficiency. The dynamic programming techniques used for solving the "travelling salesman problem" lead to significant reduction of a computational complexity of the algorithm.

In the process of network dimensioning a series of different deployment scenarios are taken into account. They differ mainly in a density of termination nodes in the distribution network. Among other parameters that can be tuned there are: target population penetration, "white", "grey" or "black" locations that should be within the coverage of the transmission network, and the maximum range of a termination node which depends on the last mile technology. Other strategic aims of the designing procedure are to ensure the broadband access for 90% households, 100% public institutions and 100% business customers by 2013.

At this stage the weights of graph edges are lengths of connections and the number of households covered by the transmission network. However, we are also going to take into account the number of business customers and public institutions where symmetrical broadband Internet service should be delivered.

Prims or Dijkstra-Prims algorithm is a greedy algorithm that finds a minimum spanning tree for a connected, weighted graph. Having an undirected and connected graph, the algorithm determines a subset E' of a set E of edges for which the graph is still connected, but the sum of costs of all edges of a set E' is the smallest possible value.

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