Paper

# A Framework for Evaluation of Communication Bandwidth Market Models

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**Abstract—The article presents a method of analysis of market-based models for resource allocation in communication networks. It consists of several stages: classification of a market model, generation of input data, data adaptation to a tested model, test calculations and, finally, presentation and interpretation of results. A set of general criteria to assess various models has been proposed. Tests are run using dedicated computer applications, data is stored in open XML-based format originated in the multicommodity market model. Network topologies are derived from the SNDlib library.**

***Keywords—auctions, bandwidth trading, resource allocation.***

## 1. Introduction

A dominant form of trading on the market of resources in telecommunications networks is bilateral contracting. Time of negotiations is undesirably long in relation to high dynamics of business processes in the telecommunications market. In addition, the bilateral nature of negotiations reduces the transparency of trade rules. This often enables network operators or service providers with significant market power to obtain better trading conditions than it is justified. Therefore, the research is conducted on innovative mechanisms for trading of transport resources in networks to enhance the efficiency of their usage and the quality of conditions of competing for them, particularly in the form of auctions and exchanges. Potential benefits of the introduction of such multilateral trading patterns on the market for telecommunications network capacity are discussed in [1], problems of the organization of network bandwidth exchanges are presented in [2].

The variety of possible models and their variants creates a problem of objective evaluation and the feasibility of mutual comparison. The models may implement many different resource allocation algorithms and apply multiple optimization criteria taking into account economic and technical constraints. The chances of a simple quantitative assessment of one model in comparison to others and indicating its advantages and disadvantages are hindered. This paper is an attempt to develop a methodological approach to testing and comparing models of market-based allocation of capacity in communication networks. The method can be helpful in choosing trade models adequate to specific markets segments in the telecommunications sector.

The structure of the article is as follows: Section 2 briefly describes the survivable network design library (SNDlib) and the multicommodity market model ($M^3$). Section 3 shows the successive stages of testing. Section 4 presents a set of comparative criteria. Section 5 shows an example of the application of the proposed framework for a selected bandwidth trading model. Section 6 summarizes the results of the research.

## 2. A Method of Analysis of Market-Based Models

The proposed approach to evaluating market models results in a multi-stage framework. The stages, shown in Fig. 1, are as follows:

- model classification,
- test data generation,
- data adaptation for a model,
- running tests,
- output data analysis.

Each step can be performed independently, using separate tools. Data passed between the successive stages is stored in text files saved in a extensible markup language (XML)-based format.

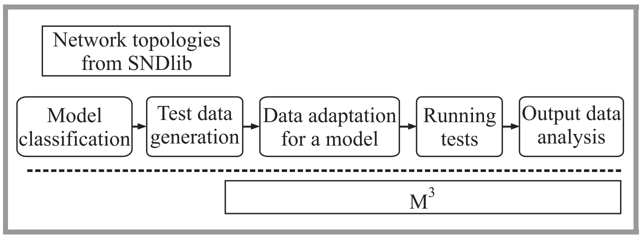


*Fig. 1.* Schema of the bandwidth model testing framework.

The proposed methodology integrates the results of other research: the data of the SNDlib and the model of a multicommodity market process ($M^3$).

### *2.1. The SNDlib Library*

The survivable fixed telecommunication network design library [3] is a scientific library sharing exemplary data for problems of the design/dimensioning of communication transport networks.

Examples stored in the library reflect the topology of real networks. All of them are saved in a standardized XML dialect. The main purpose of the library is to collect actual data on research problems and create a platform for exchange of information between scientists and engineers involved in network design. The library comprises network topologies with the structure of network links and bandwidth demands, best solutions and their dual bounds, an up-to-date bibliography and a list of conferences on the subject. The scope of solving methods is broad and includes models of linear/integer programming, branch-and-bound algorithms, column generation, a Lagrangian relaxation and meta-heuristics such as evolutionary algorithms, simulated annealing or taboo search.

### *2.2. The M$^3$ Model*

Consistent description of a broad scope of potential trade processes on the bandwidth market needs an application of an adequately flexible information model. Such flexibility and a high degree of openness can be obtained by using an information model based on the M$^3$ [4]. The M$^3$ is a set of formal models that describe data and communication messages on multi-commodity infrastructure markets. The M$^3$ model has been adopted in our research for a market of transport resources in telecommunication networks.

The M$^3$ model enables a generic description of the trading information exchanged between market participants. The data is stored in a special M3-XML dialect allowing the expression of: the existing network infrastructure, the time scale in which the trade is accomplished, the entity structure (sellers, buyers, brokers, leaseholders, etc.), the trade object structure (description of traded goods) and the offers submitted by individual market participants. It contains, in particular, descriptions of market offers: elementary (singlecommodity), integrated (multicommodity), and also grouping: describing more complex relations between elementary commodities or integrated offers with common conditions or resource constraints. The introduction of the mechanism of grouping of the offers facilitates the formulation of non-trivial constraints for each individual market participant, and proper valuation/quoting of the offers.

In practical applications one may use all or just selected elements of the M$^3$ data model. It is worth noting that the M$^3$ model and its M3-XML data format do not specify how the trade itself and the allocation of resources are realized.

## 3. Stages of Preparing and Running Tests

This section presents the sequential stages of preparation and runnig tests of bandwidth market models.

### *3.1. Classification of the Model*

The properties of models originate in economics, game theory principles of mechanism design and in technical features of traded bandwidth. Selecting distinctive features of the models creates a space for their classification and grouping. The set of the classifying features have been developed upon analysis of the network resource structure and the organization of trade processes. The categories of the network design problems from [3] have also been taken into account.

**Type of commodities**. The number of types of resources in telecommunication networks is significant: there are many technologies used in transmission systems (switching and multipexing techniques). The resources can have a physical or a virtual nature and their detailed specification depends on a layered architecture of modern networks.

Our research is focused on transport communication networks and in this context the general elementary commodity is a bandwidth of a point-to-point connection between a pair of nodes in a specified network layer. It is defined as a network capacity enabling transmission of specified data amount from a source node to a destination node during specified quantum of time.

The bandwidth of a network link can be offered for sell. The bandwidth needed to serve a traffic demand can be purchased – the existence of a direct connection between the pair of nodes of the demand is not necessary, the demand can be realized with one or more paths (consisting of sequences of links).

The trade models can take into account many of characteristic features of bandwidth commodities. The most significant ones are following:

– direction of bandwidth: bandwidth commodities can be directed, undirected (data flow is possible in both directions) or asymmetric (capacity depends on the direction of data flow); bidirectional bandwidth commodities can be modeled with two oppositely directed commodities;

– divisibility of bandwidth: bandwidth can be fully divisible, modular (divisible with the accuracy of units), unit (a particular case of modular bandwidth modeled in combinatorial auctions), predefined (divisible only within specified volumes);

– commodity structure: some trade models omit structural relations between commodities and concern trading only separate elementary commodities; other models enable trading complex structures of commodities, particularly on the demand side: the structures can refer to a set of predefined network paths, a specified set of network links or whole subnetworks (e.g., for purposes of building virtual private networks).

**Relations between offers and commodities**. The models can take into account different kinds of assignment between traded commodities and related trade offers. One can distinguish:

- elementary offers: a single offer concerns a single elementary commodity;
- bundled offers: a single offer concerns a bundle of elementary commodities, the commodities can be sold/bought in equal or different amounts.

**Market participants**. The models can describe many organizational forms of trade. The basic division takes into consideration the number and the roles of market participants. One can distinguish:

- single-side models: a market operator sell bandwidth capacity to its clients, or a single client buys services from many competing network operators;
- double-sided models: there are many buyers and sellers.

The important role in trade models is a market operator – the entity that balances the market: allocates resources and sets prices. In centralized models there is one market operator. In distributed models there can be many of them.

**Quality of service constraints**. Market contracts concerning telecommunication resources usually define a set of parameters describing the quality of service (QoS). The trade models can take those constraints into account, e.g., specifying the maximal length of a path or the maximal delay of a packet.

**Resource allocation rule**. The network resources are allocated by means of a defined algorithm operating on the available market offers. In the context of transport network resources one can distinguish the basic allocation rules:

- path setting: the required point-to-point bandwidth connections are served with paths consisting of a sequence of communication links;
- allocation of single resources: buy offers concern separate resources that is not bundled without any explicitly expressed relation.

**Pricing rule**. Market models set contract prices according to a specified rule. Some popular examples of such rules are: English auction, second-price auction, Vickrey-Clarke-Groves auction, dual pricing, etc.

**Exchanged messages**. The essential feature of a trade model is the type of signals exchanged between market participants and a market operator. The signals can have various forms:

- point characteristics: a traditional market offer indicating commodities, their amounts and offer prices;
- partial characteristics of preferences, e.g., a set of points from utility function or a stepwise offer;
- full characteristics of preferences, e.g., in the form of an utility function.

**Market balancing dynamics**. The models can be divided according to the time schedule of the market balancing process. One can distinguish two basic classes:

- one-time auctions: market participants submit their offers and then a market operator allocates resources and sets prices taking into account all submitted offers;
- iterated auctions: the final market balance is achieved in a sequence of steps, in which market participants can modify their signals submitted to a market.

**Implementation**. The models can be implemented with many different techniques and tools originated in operations research, computer programming and mathematics. Examples of the implementation types are following: linear programming, mathematical programming, dynamic programming, parametric equations, heuristics, etc.

### *3.2. Input Data Generation*

One of the purposes of the research presented in this paper is to create a library of test examples for the scientific community involved in the design of market algorithms and models for communication transport networks. Input data for test cases should reflect the size of demand and supply observable in the real network bandwidth market. The test data used for the research may come from the following sources:

- examples of network design problems;
- economic models of supply and demand;
- real data from the telecommunications market.

Trade patterns for transport resources of networks and balancing market offers are conceptually similar to the problems of network design – the relationship between trade mechanisms and designing the network have been discussed in [5]: the demand for network bandwidth and communication links between nodes can be interpreted as a market offer to buy/sell network resources. In order to generate a test network topology and market offers one can therefore use the data from the SNDlib library. The examples from the database cannot be used directly due to their important constraints. Firstly, there is only one link between pairs of nodes in a network topology, while the market models assume the existence of multiple offers on the bandwidth segment between a pair of nodes (a similar requirement applies also to buy offers). Secondly, any pricing information in the examples of the SNDlib is only expressed by determining the cost of installation and expansion of links, while in the trade models one requires the price of bids submitted by buyers and sellers. All the missing elements can be added to the original network design examples, e.g., by means of the pseudo-random generation adjusted to the specific test case.

The second source of the data on the potential offers on the bandwidth market is the use of economic models of supply and demand. Such models in the context of resources in telecommunication networks are under research, especially in the field of modeling network traffic and demand for services. Some analysis of supply and demand can be transferred to the ground of telecommunications from other infrastructure markets such as energy or transportation.

The test data can also come from the analysis of the actual data on transactions accomplished in the real telecommunications market. Acquiring such data is difficult in practice because there are not any network bandwidth exchanges operating on a larger scale, and the information about bilateral contracts between telecommunications companies is generally private and not publicly available. However, there are some internet sites showing examples of bandwidth prices in certain local markets, e.g., the U.S., and reports on global trends in the development of the telecommunications market, such as the work [6].

### *3.3. Data Adaptation – Conversion to $M^3$ Format*

The adopted information model for the framework is the $M^3$ – any data of test cases should be saved in the M3-XML format. This can be achieved in two ways.

The first one is the direct generation of input data in the desired format. This requires dedicated computer tools allowing editing or automatic generation of the test data.

The second approach assumes the use of examples contained in the SNDlib library enriched with the entity structure, the object structure and trade offers. Choosing an XML dialect as a data format results in the opportunity to use widely available read/write software libraries for many programming languages, which facilitate the development of new tools for test data generation. The natural way to transform XML data into another format is the use of a extensible stylesheed language transformation (XSLT) [7]. One can also use the query language XQuery [8].

For the purpose of this research a mixed approached has been adopted. A dedicated computer program with a graphical user interface has been designed and implemented. It has been used to enrich the SNDlib examples with lacking elements and save them in the simple dedicated bandwidth market XML (BM-XML) format describing the network nodes and the offers for sale and purchase of network capacity. A series of XSLT transformations processing the BM-XML format into M3-XML format have been used. In this way we have obtained a convenient set of computer tools used for importing and converting examples of network topology to the new library of complete test cases for bandwidth market models.

### *3.4. Running Tests*

The next step is to run required calculations of network capacity allocation and pricing for a tested model with the prepared data. It is assumed that all the input data is stored in the M3-XML format. Therefore any market mechanism, which is a subject to the tests, should be able to read input data and generate output data compatible with the $M^3$ information model. The flow of data during the execution of the tests is illustrated in Fig. 2.

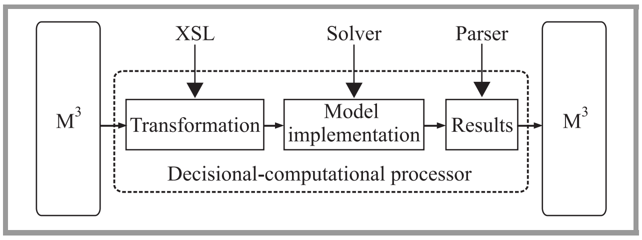


***Fig. 2.*** M3-XML format data flow in running tests.

The concept of a universal decisional-computational processor has been developed [9] and the initial implementation has been made: it solves the tasks described by the data stored in M3-XML format. The corresponding XSLT transformation converts the data to the internal representation of the appropriate model. The processor returns the data in the M3-XML format. Such modular architecture allows independent implementation of the trade models from the evaluation framework: compatibility with the $M^3$ information model can be achieved by the input and output interfaces. The XSLT transformations can be applied to convert the input data into the format required by the particular computing processor, e.g., a standard mathematical programming solver or a dedicated implementation of the algorithm of a trade model. Examples of such transformations have already been created [4] and they are further extended in our research on new trading models. They convert the data in M3-XML format into GMPL format (gnumath programming language) [10], which can be used by optimization solvers, e.g., GlpSol and AMPL (a mathematical programming language). Linear models can also be easily converted to other LP (linear programming) formats, e.g., the one used by the CPLEX solver.

### *3.5. Analysis of Output Data*

The next step to take after having completed series of computational experiments is to analyze the obtained results. The application of the $M^3$ information model to describe the output of the tested models facilitates the analysis. If one had different data formats for various trade models the comparison of the results would be much more difficult and time-consuming. The adopted XML-based format allows for simple data conversion to other formats for presentation purposes, such as exporting to spreadsheets or graphical visualization applications.

## 4. Comparative Criteria

A fundamental part of the evaluation framework is the proper selection of indicators. Trade models are often designed for a specific market context and defined aspects of resource allocation, so the comparative criteria should be general enough to be applicable to most of them. We propose a set of such indicators, they represent measures originating in economics, game theory and technical efficiency.

A properly designed trade model should strive to meet several desirable properties that make it attractive for a wide range of market participants (traders, decision makers, regulators). These properties can be used as evaluation criteria providing information about the "quality" of a given model. The set of criteria is divided into three categories: global, individual and technical. The division into the individual and global ones expresses the natural market game between individual participants' interests and global interests. The third category aims in evaluation of the models in terms of their technical efficiency.

### *4.1. Global Criteria*

**Economic efficiency**. The main measure of economic efficiency is the market surplus. It is defined as the aggregated economic benefits derived from the market exchange of goods. If the market mechanism encourages participants to submit truthful bids, then economic prosperity could be determined accurately using actual bids. If the market offer does not comply with the participant's preference profile, it can be used only as an imprecise measure known as economic benefits. It is the difference between total value of goods purchased and the total value of goods sold on the market, as follows:

$$Q = \sum_{m \in B} d_m e_m - \sum_{l \in S} p_l s_l \,, \tag{1}$$

where $e_m$ is the unit offer price of buy offer $m$, $d_m$ is realized bandwidth of buy offer $m$, $s_l$ is the unit offer price of sell offer $l$, and $p_l$ is realized bandwidth of sell offer $l$.

**Incentive compatibility**. The incentive compatibility property holds if no market participant has incentives to report signal different from its type/preferences: no agent has incentives to report an untruthful offer.

Incentive compatible mechanism prevents strategic actions of the participants. The measure of the effectiveness of the mechanism against strategic players is the allocative inefficiency ($AI$) defined as follows:

$$AI = \frac{Q^0 - Q}{Q^0} 100\% \,, \tag{2}$$

where $Q^0$ is the economic surplus if every market participant submits a truthful bid, $Q$ is the actual (achieved) value of the economic welfare, where participants can submit bids incompatible with their preferences. It should be noted that the participants may submit bids incompatible with their profile of preferences in order to achieve higher profits.

**Budget balance**. A trade model has balanced budget if sum of sellers' expenses is equal to sum of buyers' incomes: there is no need to surcharge the trading mechanism, and the mechanism does not earn additional profits.

The first quantitative measure describing this criterion is the value of the difference between total sellers' income $SI$ and total buyers' expense $BE$ related to the total market value. This measure has got the term budget imbalance in relation to total turnover ($RBIT$):

$$RBIT = \frac{SI - BE}{SI + BE} 100\% \,. \tag{3}$$

The second measure describing the budget balance criterion is the value of the difference between total sellers' income and total buyers' expense related to the market surplus. This measure has got the term budget imbalance in relation to market surplus ($RBIS$):

$$RBIS = \frac{SI - BE}{Q} 100\% \,. \tag{4}$$

**Pareto-efficiency**. The results given by the trading model are Pareto-efficient, if one can not improve the result for one market participant without making some other participants worse off: the results are Pareto-efficient if such results are not Pareto-dominated by other results.

### *4.2. Individual Criteria*

**Individual economic benefits**. From the perspective of an individual market participant the trading model should allow to obtain the highest possible value of the individual economic benefits. The measure is defined as the value of the individual utility function for each market participant.

**Absolute individual fairness – individual rationality**. A trade model is individually rational, if no market participant loses from the participation in the trade. This property is also called the voluntary participation (if it may lose then it can choose not to participate in the trade).

**Relative individual fairness**. A trade model is fair in a relative sense, when from the perspective of each participant no other offer is favored in relation to its offer.

Other criteria related to fairness have been outlined below:

– anonymity: a participant remains anonymous if renumbering of participants does not affect the obtained outcome;

– symmetry: two participants with the same parameters, in the same market situation (the same utility functions) should obtain the same individual results;

– an equal price: each participant receives the same volume of a commodity for the same unit price.

### *4.3. Technical Efficiency*

The possibility of a practical technical implementation of the trade model is evaluated with technical efficiency indicators dependent on the computational complexity of the model and on its reliability. Exemplary measures are:

– duration of single market balancing;

– total duration of the market balancing (for iterative mechanisms);

– a number of exchanged messages (total, average).

## 5. Example

The evaluation framework has been applied to test the balancing communication bandwidth trade (BCBT) model discussed in [5]. It is a multicommodity trade model for the market of network transport resources with many buyers and many sellers. The model assumes complete divisibility of offered bandwidth (sell offers) and the ability to allocate any fraction of bandwidth to any bandwidth demand (buy offers). The market balancing process consists of setting the paths serving buy offers with a combination of sell offers. The formal format of the model is a linear programming problem representing a double auction with the maximization of market welfare.
The evaluation of the properties of the BCBT model has been carried out according to the framework principles outlined in the paper. Below a brief description of this test case is presented.

### *5.1. Classification of the Model*

**Type of commodities**. The BCBT model assumes that both links (sell offers) and paths (buy offers) concern unidirectional network capacity. The division model of the offered bandwidth is continuous: the seller and buyer may indicate bandwidth amount of their bids with any positive real number. The bandwidth can be traded in the range from 0 to a maximal admissible volume specified for the offers.

**Relations between offers and commodities**. All market offers in the model are elementary offers concerning elementary point-to-point bandwidth connections in the network.

**Market participants**. The model represents a double auction: there are many buyers and many sellers. It is a centralized trading model – a single market operator balances the market.

**Quality of service constraints**. There are not any QoS parameters included in the model (e.g., there is no limit on the maximum length of paths).

**Resource allocation rule**. The balancing mechanism can freely allocate bandwidth in the network, in particular a single sell offer can be used to serve multiple buy offers, a single buy offer can be realized with many paths. There are no restrictions on the possibility of setting paths in the network: there are no predefined paths, they are set during the market balancing process taking into account of all available offers.

**Pricing rule**. The pricing rule adopted is the dual pricing rule – it is based on dual prices of the balance constraints. In the BCBT model the balance constraints exist only for the links – so the prices are determined directly for the sell offers only. The prices for demands (buy offers) are determined as a sum of the values of bandwidth bought on links in the related paths.

**Exchanged messages**. The messages exchanged in the model are point characteristics of market participants' preferences in the form of a traditional offer expressing the amount of commodities and their unit prices.

**Market balancing dynamics.** The model is an example of a one-time double auction – the market participants submit offers and then the market is balanced – resources are allocated and prices are calculated.

**Implementation**. The model has been implemented as a linear program maximizing total market welfare. The linear program is written in GMPL and AMPL.

### *5.2. Input Data*

The network topology is derived from the example of the NOBEL-EU network from the SNDlib developed in the IST NOBEL project "*Next Generation Optical Networks for Broadband European Leadership*" [11]. The nodes of the network are located in 28 major European cities. The network topology (nodes and potential links) is illustrated in Fig. 3.

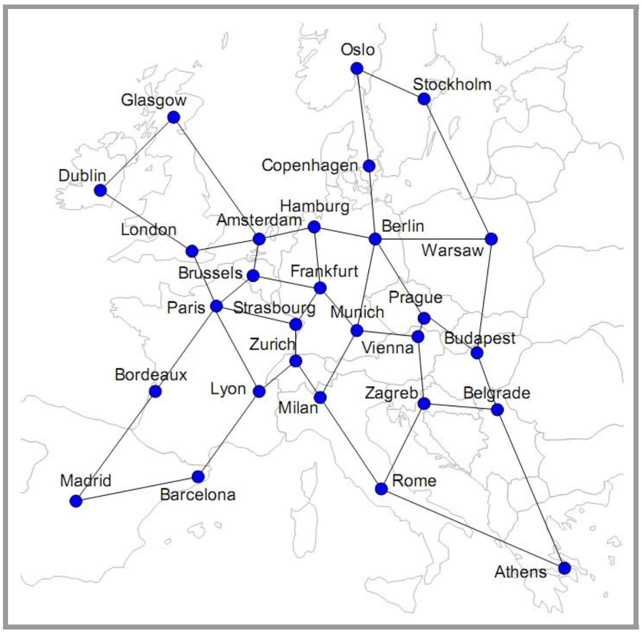


***Fig. 3.*** Pan-European network of EU project IST NOBEL [11].

Bandwidth buy offers are independent from the traffic demands included in the original SNDlib example. It is assumed that the offered prices rise along with the geographical distance between a pair of nodes, and offered bandwidth capacity decreases with the distance. 150 buy offers have been generated by the following algorithm:

1. Draw randomly a source and a destination network node (different from each other).
2. Set pseudo-randomly offer price according to the expression (5) with dependency on the geographical distance between the nodes:

$$\mathrm{Gauss}\left(\mathrm{Avg}P \cdot Dist,\ \frac{\mathrm{Avg}P}{3Dist}\right). \tag{5}$$

3. Set pseudo-randomly offer bandwidth capacity according to the expression (6) with dependency on the geographical distance between the nodes:

$$\mathrm{Uniform}\big(0.5\,\mathrm{Avg}C,\ 1.5\,\mathrm{Avg}C\big)\left(1 - \frac{Dist}{Dist_{\max}}\right) \tag{6}$$

with the following denotation:

– $\mathrm{Gauss}\,(a,b)$: Gaussian distribution with the expected value $a$ and the standard deviation $b$;

– $\mathrm{Uniform}\,(a,b)$: uniform distribution in the range $[a,b]$;

– $\mathrm{Avg}P$: average unit bandwidth price related to a unit distance;

– $\mathrm{Avg}C$: average bandwidth capacity for adjacent nodes (distance equals 0);

– $Dist$: distance between nodes;

– $Dist_{\max}$: the maximal distance between the nodes in the network.

Following parameter values has been used for buy offer generation: $\mathrm{Avg}P = 1$, $\mathrm{Avg}C = 15$.
Sell offers have been also generated randomly (they have replaced links in the original SNDlib example: the primary links have been interpreted as bandwidth segments on which sell offers are submitted). The assumption made is similar to the case of buy offers: the offered prices rise along with the geographical distance between a pair of nodes, and offered bandwidth capacity decreases with the distance. 5 separate sell offers have been generated on every bandwidth segment using the same mathematical expression for setting prices and capacities as for the buy offers (with the following parameter values: $\mathrm{Avg}P = 0.5$, $\mathrm{Avg}C = 10$) according to the algorithm:

1. Set pseudo-randomly the direction of the offer (the probability of each direction equals 0.5).

2. Set pseudo-randomly offer price according to the expression (5) with dependency on the geographical distance between the nodes.

3. Set pseudo-randomly offer bandwidth capacity according to the expression (6) with dependency on the geographical distance between the nodes.

The test data generated for the Nobel-EU network including 150 buy offers and 205 sell offers has been saved in a BM-XML format file. The data sat is a simple but complete test case, and it can be used also for testing the properties of other models than the BCBT.

### *5.3. Adaptation and Running Tests*

A single test procedure consists of three phases. The first one is the adaptation of the data stored in BM-XML format to the M3-XML format. The second phase is the solution of the problem in accordance with a given mathematical model of the BCBT. The third phase is the collection of the results and their analysis. The detailed description of each step is as follows:

- The data in the BM-XML format has been converted to the $M^3$ information model using several XSLT transformations. The result of this procedure is a set of files in the M3-XML format.

- The obtained data set is then passed to the decisional-computational processor performing the following steps: the data is converted to a GMPL model implementing the BCBT allocation model using an XSLT transformation; the complete GMPL model with numeric data is passed to a linear programming solver (e.g., AMPL, GlpSol) returning results.

- The results are parsed to the M3-XML format.

Calculations have been performed on a PC (Intel Core 2 Duo 2.60 GHz, 2 GB RAM).

### *5.4. Output Data Analysis*

The numerical data and short comments for the framework indicators have been presented below.

**Economic efficiency**. From a global perspective the BCBT model is economically efficient in the sense that it maximizes the global economic welfere. Thus, for given market offers, no better allocation of bandwidth resources is possible. The market welfare achieved in the test case is 13861.

**Incentive compatibility**. The obtained value of the allocative inefficiency equals 0.026. It is a very good outcome – it indicates that the possibility for speculation on the market is limited.

**Budget balance**. The RBIT and RBIS benchmarks are 0, so the model fulfills the requirements for the budget balance property.

Pareto-efficiency. The Pareto-efficiency property holds for the family of BCBT models. Pareto-efficiency is ensured if the aggregation function of the individual objective functions is strictly increasing. The family of BCBT models uses objective function as the sum of individual objective functions, which is strictly increasing with respect to every coordinate, so the whole BCBT family is Pareto-efficient.

**Individual economic benefits**. The calculated contract prices have been used to determine the individual benefits of the market participants. The list of their values has not been included here because of the limited space of the paper.

**Absolute individual fairness – individual rationality**. The individual benefits for those market participants, whose offers have been successfully traded, are positive. So the requirements of the individual rationality property are fulfilled.

**Relative individual fairness**. The requirements for relative fairness of individual market participants are partially met in the test case. In general their fulfilment depends on the implementation of solvers (e.g., the order of identical market offers may have impact on the volume of their realization). The BCBT model itself does not have any additional constraints for complying with these requirements.

**Duration of market balancing**. The total time of the market balancing has been very short: 0.95 s. There have not been any additional computation for resource pricing because the prices have been derived from the parameters of the linear program solution. The LP formulation of the BCBT model does not comprise integer variables, to it is feasible even for large networks.

**Number of exchanged messages**. The market participants have submitted 150 buy and 205 sell offers – there are total 355 bid messages (the same number of messages covers announcing the results of the trade).

## 6. Summary

The paper presents an attempt to develop a methodological approach to the problem of comparing different models for trading capacity in the communication transport networks. Several stages of test preparation and running computations have been distinguished and described. The use of standardized data format is essential: the task of comparison of results becomes easier and the same test cases can be reused for many models. The proposed framework will be used to study and compare the properties of different trade models, such as c-SeBiDA (combinatorial sellers' bid double auction) [12], MIDAS [13], BCBT [5], NSP (network service provider) [14], and other new models developed by the authors in their research. The described framework and its tools can be a part of a broader research platform forming an advanced computing environment for testing the market models of resource allocation in communication networks.

The evaluation framework is in its early stage and still there is a need to refine many of its elements. The most important areas perceived for improvement include:

- The development and extension of economic models to describe the bandwidth demand and supply enabling generation of test data reflecting the real market conditions.
- Refine the set of criteria enabling to study and compare specific characteristics of trading models, e.g., resulting from the market game between trade participants.

These and other extensions of the basic methodology proposed in this paper will be presented in the authors' future papers.

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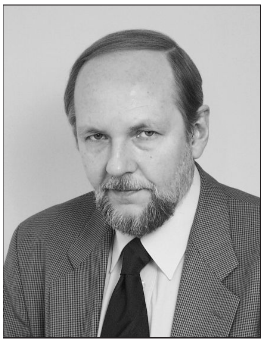

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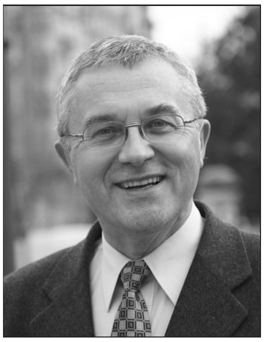

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