Quality of Multicast Trees in Ad-Hoc Networks

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***Abstract*—Wireless ad-hoc networks are playing an important role in extending the implementation of traditional wireless infrastructure (cellular networks, wireless LAN, etc). Network topology planning and performance analysis are crucial challenges for network designers (i.e. routing design in ad-hoc networks is a challenge because of limited node resources). Routing design in ad-hoc networks is a challenge because of limited node resources. Thus efficient data transmission techniques like multicasting regarding quality of service requirements are under scrutiny. The article analyzes and explores the performance of multicast heuristic algorithms and quality of multicast trees in ad-hoc networks.**
Keywords. ad-hoc networks, topology generator, MANET, multi-hop networks

I. Introduction

Ad-hoc networks consists of collection of nodes placed in different geographical locations with wireless communication between them. The most distinct feature that differs them from other networks is lack of cable infrastructure – the structure is quite decentralized. Nodes in ad-hoc network can work as clients or as routers. Last few years show increased use of ad-hoc networks. They are used in military and civilian usage (on much smaller scale – used by rescue team, police or commercially by phones or computers equipped in UMTS and GPS devices). In some measurement systems nodes can represent an autonomous sensors or indicators. Ad-hoc networks can be also used to collect of sensor data for data processing for a wide range of applications such as tensor systems, air pollution monitoring, and the like. Nodes in these networks generate traffic to be forwarded to some other nodes (unicast) or a group of nodes (multicast).

Mobile ad-hoc networks (MANET) and mesh networks are closely related, but MANET also have to deal with the problems introduced by the mobility of the nodes (nodes may represent mobile devices). Similarly to the mesh networks, nodes act both as an end system (transmitting and receiving data) and as a router (allowing traffic to pass through) resulting in multi-hop routing. Networks are *in motion* – nodes are mobile and may go out of range of other nodes in the network.

As of today, ad-hoc networks can work in two modes: *single-hop* and *multi-hop* [3]. In *single-hop* mode, all nodes are in direct range of another node. Communication between them is possible without any external routing device. *Multi-hop* networks have the ability to be communicate and use routing device at one time. This approach improves speed of transmission and is prone to danger of losing connection. Mobility of nodes and devices multiplies problems with stability and quality of transmission.

The implementation of multicasting requires solutions of many combinatorial problems accompanying the building of optimal transmission trees [21]. In the optimization process it can be distinguished: MST (*Minimum Steiner Tree*), and SPT (*Shortest Path Tree*) – tree with the shortest paths between the source node and each of the destination nodes. Finding the MST, which is a $\mathcal{NP}$-complete problem, results in a structure with a minimum total cost. The relevant literature provides a wide range of heuristics solving this problem in polynomial time and dedicated mostly for paket networks [16], [27], [18], [19], [20]. In case of MANET multicast protocols, two basics architectures are used: tree-based protocols, where MAODV (*Multicast Ad-hoc On-demand Distance Vector routing*) [22] is the most discussed tree-based protocol and mesh based protocol: ODMRP (*On-Demand Multicast Routing Protocol*) [23].

The main goal of this article is to determine representative network parameters as average node degree, clustering coefficient and diameter, and examine their values in ad-hoc networks. Literature confirms dependencies between network topology parameters and efficiency of routing algorithms [14], [8]. The analysis of the effectiveness of the routing algorithms known to the authors and the design of the new solutions utilize the numerical simulation based on the abstract model of the existing network. These, in turn, need network models reflecting in the best adequate way the ad-hoc network. Thus new fast generator for ad-hoc networks has been proposed in the article.

The article structure is as follow: Chapter 2 describes network topology, its parameters and multicast optimization algorithms. Chapter 3 presents simulation study regarding authors' ad-hoc topology generator. Chapter 4 presents simulation results. The final chapter sums up the discussion.

II. Network model

A. Graph model

Let us assume that a network is represented by an undirected, connected graph $N = (V, E)$, where V is a set of nodes, and E is a set of links. The existence of the link $e = (u, v)$ between the node u and v entails the existence of the link $e' = (v, u)$ for any $u, v \in V$ (corresponding to two-way links in communication networks). With each link $e \in E$, two parameters are coupled: cost $c(e)$ and delay $d(e)$. The cost of a connection represents the usage of the link resources. $c(e)$ is then a function of the traffic volume in a given link and the capacity of the buffer needed for the traffic. A delay in the link $d(e)$ is, in turn, the sum of the delays introduced by the propagation in a link, queuing and switching in the nodes of the network.

B. Propagation model

Ad-hoc network topologies are analyzed in many works, including [4] and [5]. These publications provide detailed analysis on modeling topologies for ad-hoc networks, methods for controlling topologies, models of mobility of nodes in networks and routing protocols in wireless ad-hoc networks. Ad-hoc networks are formed by devices that have mobile energy source with limited capacity. It is essential then for the energy consumption to be maintained at a possibly low level in order to prolong the time duration of autonomous operation of the device.

The adopted model of the costs of links between the devices takes into consideration energy used by the antenna system of a device. The proposed implementation assumes that network devices have isotropic radiators. The power of electromagnetic wave P_r received by the antenna can be expressed by the following dependency:

$$P_r \sim \frac{P_s}{d^\alpha}, \tag{1}$$

where d expresses the distance between the transmitter and the receiver, and P_s denotes transmitting power. If radiation propagates in vacuum, then $\alpha = 2$. However, in real environment $\alpha \in \langle 2, 6 \rangle$ [5]. In the present investigation, the value $\alpha = 3.5$ was adopted. This value was calculated as an arithmetic mean from the middle ranges of the variability of the parameter α, published in [5] and [4]. The required power of the received electromagnetic wave P_r was adopted as constant.

For simplicity, this model bases on the pathloss power law model for radio propagation. With the power law model for radio propagation, and the assumption that transmission power and receiver sensitivity for all nodes is same, the coverage area of any node is a circle with radius r. A node can have direct communication with all nodes that fall inside its coverage area [6].

C. Network parameters

To evaluate different structures of ad-hoc networks it is important to define basic parameters describing network topology:

- *average node degree* [14]:

$$D_{av} = \frac{2k}{n} \tag{2}$$

  where n – number of nodes, k – number of links,
- *hop diameter* [14] – the length of the longest shortest path between any two nodes; the shortest paths are computed using *hop count* metric,
- *clustering coefficient* (γ_v) of node v is the proportion of links between the vertices within its neighborhood divided by the number of links that could possibly exist between them [15].
  Let $\Gamma(v)$ be a neighborhood of a vertex v consisting of the vertices adjacent to v (not including v itself). More precisely:

$$\gamma_v = \frac{|E(\Gamma(v))|}{\binom{k_v}{2}} = \frac{2|E(\Gamma(v))|}{k_v(k_v-1)}, \tag{3}$$

  where $|E(\Gamma(v))|$ is the number of edges in the neighborhood of v and $\binom{k_v}{2}$ is the total number of possible edges between neighbourhood nodes.
  Let $V^{(1)} \subset V$ denotes the set of vertices of degree 1. Therefore [2], [13]:

$$\hat{\gamma} = \frac{1}{|V| - |V^{(1)}|} \sum_{v \in V \setminus V^{(1)}} \gamma_v. \tag{4}$$

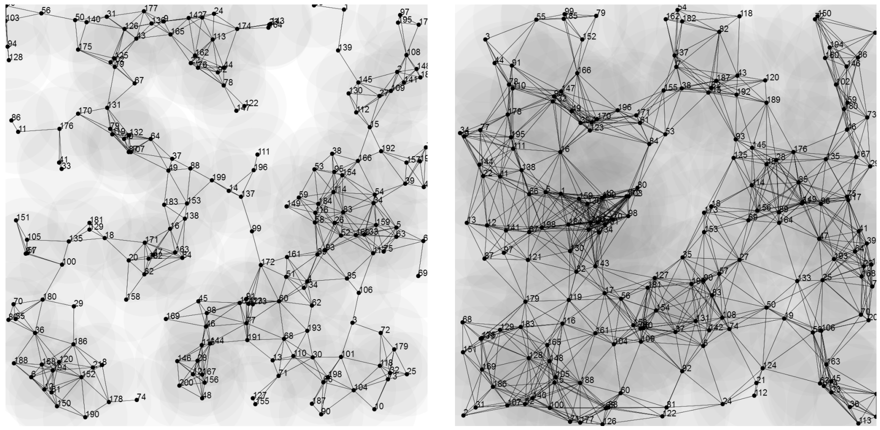
  Clustering coefficient quantifies how well connected are the neighbours of a vertex in a graph. In real networks it decreases with the decreasing value of vertex degree.

D. Multicast optimization

The simplest heuristic approach, solves the *Minimum Steiner Tree* problem with delay costraint called the *Constrained Shortest Path Tree* (CSPT), and relies on computation the shortest paths between the source and receivers. Individual paths have the minimum length, but multicast distribution tree created this way is not optimal. Wang et al. proved that if network links contain at least two additive metrics, then QoS routing is $\mathcal{NP}$-complete problem [24].

The KMB heuristics (Kou, Markowsky, Berman) [25] is one of the best known heuristics solving the problem of the minimal Steiner tree. It is also very effective as far as the accuracy of the solution is concerned [26] and its computational complexity is $O(|M||V|^2)$. This heuristics is the basis for the KPP algorithm (Kompella, Pasquale, Polyzos) [27] that, additionally, takes into consideration the delay constraint. During the first phase of the KPP, a complete graph is constructed whose all vertices are the source node s and the destination nodes $m_x \in M$, while the edges represent the least cost paths connecting any two nodes a and b in the original graph $G = (V, E)$, where $a, b \in \{M \cup s\}$. Then, the minimal spanning tree is determined in this graph taking the delay constraint Δ into consideration, and then the edges of the obtained tree are converted into the paths of the original graph G. Any loops that appeared in this formed structure are removed with the help of the shortest path algorithm, for instance, by Dijkstra algorithm [28]. The computational complexity of the algorithm is $O(\Delta|V|^3)$.

The operation performed by *Multicast Lagrange Relaxation Algorithm* (MLRA) proposed by authors in [29] consists in determining the shortest path tree between the source node s and each destination node m_i along which the maximum delay value (Δ) cannot be exceeded. Path is calculated with



(a) (b)

Fig. 1. Visualization of ad-hoc networks with 200 nodes obtained using the proposed generator for $r = 100$ units (a) and $r = 150$ units (b)

an application of Lagrange relaxation algorithm refers to idea proposed by Jüttner [31]. This algorithm relay on minimizing aggregated cost function: $c_\lambda = c + \lambda d$. In each iteration of algorithm, the current value of λ parameter is calculated, in order to increase the dominance of delay in the aggregated cost function, if the optimum solution of c_λ meets the delay requirements (Δ).

The paths is determined one by one are then added to the multicast tree. If there is at least one path that does not meet the requirements, multicast tree cannot be constructed. Since the network structure created in this way may contain cycles, in order to avoid them Prim's algorithm was used [30].

III. Simulation study

Computer simulation lets turn concepts into more realistic scenarios. It allows to verify ad-hoc models and concepts without the need to implement them in hardware, yet providing a detailed insight. Therefore, authors conducted their custom-made ad-hoc generator prepared in C++, PHP [11] and SVG [12] especially for the task studies.

Generator is divided into two parts. First one is a PHP script used to convey data between user and C++ CGI applications. PHP and SVG are both used for network topology visualization. Second part consists of independent, C++ based applications that are used to quickly generate data. Dividing the generator into two parts gives much better speed than in the case the computing is done by the web server.

Network topologies are prepared with a pseudorandom two dimensional uniform distribution generator (LCG) [10]. The simulation area is a rectangle of 1,000 by 1,000 units where nodes are deployed on a mesh with the granularity of one unit. The maximum radio range of a sensor node is set to 200 units. The proposed generator simplifies network topology model – it provides ad-hoc topologies without nodes mobility.

Figures 1(a) and 1(b) are exemplary visualizations of ad-hoc networks obtained using the proposed generator for $r = 100$ units and $r = 150$ respectively. The second network has higher average node degree.

IV. Simulation results

In the first phase of the experiment (Fig. 2) distribution of node outdegree for ad-hoc network with $n = 200$ (histograms) were examined for the networks topologies presented on Fig 1. The range r (representing transmission power level) has significant influence on outdegree distribution. For $r = 100$ network represented by undirected graph contain *leaves* – nodes with outdegree equal 2 (5 nodes). Small value of node outdegree is also noticeable (43% nodes have outdegree from the range of 2 to 10). Node outdegree increases with the increasing value of r (for $r = 150$ network has no leaves and there are 7 nodes with outdegree 42 and 43). Further increasing the radio range constructs full-mesh networks (histogram with one, high outdegree peak).

In the second phase of the experiment average node degree (D_{av}), average clustering coefficient ($\hat{\gamma}$) and hop-diameter were examined in relation to the radio range (r). Increasing value of r (Fig. 3(a)) results in increasing average node degree (270% increment of D_{av} is observable for r from the range of 100 to 200). Average clustering coefficient ($\hat{\gamma}$) is differentiated when radio range $r = 100$ and networks have different number of nodes n (Fig. 3(b)). For $r > 170$ average clustering coefficient has the same values independent of number of network nodes n. Increasing value of r results in decreasing hop-diameter (Fig. 3(c)). Hop-diameter value is biggest for $n = 100$ and $r = 100$ (small networks with small radio ranges).

In order to reliable comparison of multicast algorithms into network topologies with different properties, a flat random graph constructed graphs according to the Waxman method was used [1]. This method was also adopted in author's simulation application.

Due to a wide range of solutions presented in the literature of the subject, the following representative algorithms were chosen: KPP [27] and CSPT [16] algorithms and MLRA algorithm proposed by authors [29]. Such a set of algorithms includes solutions potentially most and least effective in terms

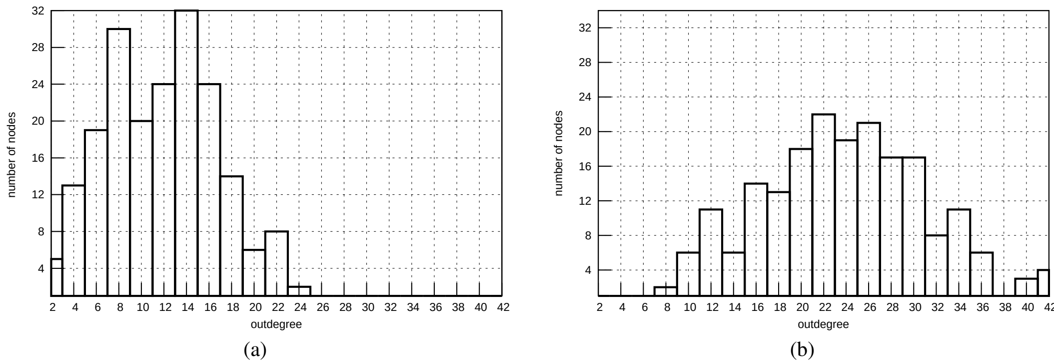
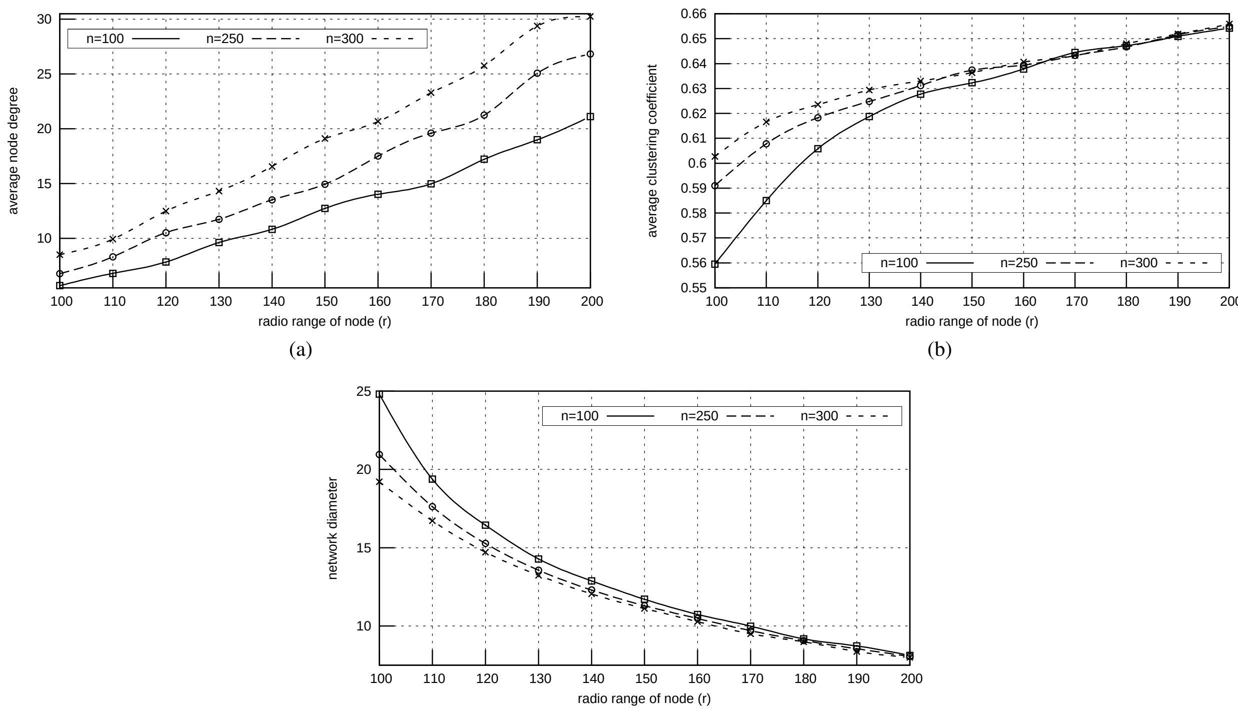


Fig. 2. Distribution of node outdegree for ad-hoc network with $n = 200, r = 100$ (a) and $n = 200, r = 150$ (b)



(c)

Fig. 3. Average node degree (a), average clustering coefficient (b) and network diameter (c) versus to the radio range of node (r)

of costs of constructed trees. This, however, will make the results of the comparison more distinct, even with comparisons with the applications of different methods of generating network topologies (random graphs and ad-hoc structures).

In the first phase of the experiment (Fig. 4(c)–4(a)) the dependency between the average cost of the constructed trees with an application of abovementioned algorithms and the maximum delay Δ was examined. The influence of the β parameter in Waxman model results in obtaining trees with lower costs with decreasing value of β. The costs of obtained trees are smallest in ad-hoc networks for all examined algorithms.

The KPP algorithm constructs multicast trees with the total cost of 37% lower in grid networks, on average, as opposed to the same algorithm implemented in Waxman networks with $\beta = 0.95$, and 22% in Waxman networks with $\beta = 0.05$ respectively. CSPT algorithm creates multicast trees with highest costs on average.

The simulation outcomes presented in the paper are the average results computed for many independent simulation iterations (Fig. 1). The values of the simulations have 95% confidence intervals calculated after the t-Student distribution. The confidence intervals are so small that, for most of the cases, they are within measurement points shown in the figures. For the sake of readability and convenience they are not shown in the graphs.

V. Conclusions and future work

The article defines representative network parameters as average node degree, clustering coefficient and diameter, and

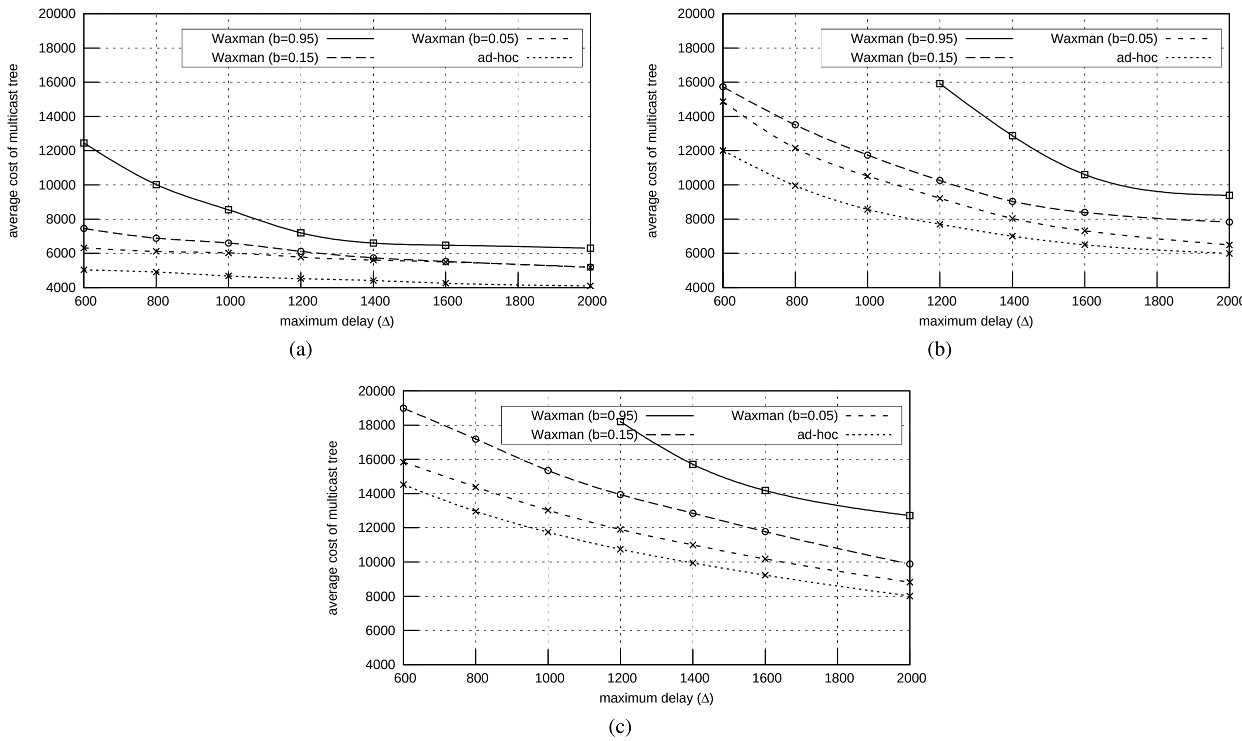


Fig. 4. Average cost of multicast tree obtained with an application of KPP (a), MLRA (b) and CSPT (c) algorithm in relation to the maximum delay Δ ($n = 100$, $k = 400$, $m = 20$)

examine their values in ad-hoc networks. Thus new fast generator for ad-hoc networks has been proposed in the article. Previous authors' works show strong influence between basic network parameters and results of routing algorithms [8], [9]. There is a need to confirm these tendencies in ad-hoc networks.

The survey of literature shows proposals of many routing protocols designed for mesh networks. Unicast protocols are dominating set of whole routing solutions while multicast routing algorithms and protocols for QoS networks are in minority and they are still an open topic. Authors evaluate multicast routing algorithms that were designed especially for packet networks with Internet-like topologies and were implemented in ad-hoc networks. The results of algorithms obtained in these networks were compared with the results obtained in random graphs (according to the Waxman model). Conducted studies confirmed the effectiveness of examined heuristic algorithms in ad-hoc topologies.

The simulation research methodology proposed earlier [20], [32] permit to model networks with wide range of nodes and many network topology parameters. This will constitute the next stage in the authors' research work aiming to define a methodology for testing multicast heuristic algorithms in ad-hoc networks and compare their efectiveness with dedicated algorithms and protocols.

Authors believe that the inclusion of the methods of mesh topology generation as well as the basic parameters of the test network are necessary conditions to have the existing and new multicast routing algorithms compared in a reliable way.

For the purposes of the study, it is assumed that future, far more advanced, devices will have the capability of precise fine tuning of the transmitting power level to that required by the receiver. It is an interesting of further research work to extend proposed generator to model the direction and transmitting power level of each node.

REFERENCES

[1] Waxmann B. Routing of multipoint connections. IEEE Journal on Selected Area in Communications, 6:1617–1622, 1988.

[2] Bu T., Towsley D. On distinguishing between Internet power law topology generators. In: Proceedings of INFOCOM 2002

[3] Conti M, Crowcroft J, Passarella A. Multi hop Ad hoc Networks from Theory to Reality. In: EURASIP Journal on Wireless Communications and Networking, special issue vol. 2007

[4] Rajaraman R. Topology Control and Routing in Ad Hoc Networks: A Survey. In: ACM SIGACT News, vol. 30, pp. 60–73, 2002.

[5] Santi P. Topology Control in Wireless Ad Hoc and Sensor Networks. In: ACM Computing Surveys, vol. 37, pp. 164–194, 2005.

[6] Grover P, Gupta N, Kumar R. Calculation of Inference in Ad-Hoc Network. In: Journal of Theoretical and Applied Information Technology, Vol. 16, No. 2, pp. 105–109, 2010.

[7] Zegura EW, Calvert KL, Bhattacharjee S. How to Model an Internetwork. In: IEEE INFOCOM '96, 1996.

[8] Piechowiak M, Zwierzykowski P. The Influence of Network Topology on the Efficiency of Multicast Heuristic Algorithms. In: Proceedings of The 5-th International Symposium – Communication Systems, Networks and Digital Signal Processing CSNDSP 2006, pp. 115–119, 2006.

[9] Piechowiak M, Zwierzykowski P. Performance of Fast Multicast Algorithms in Real Networks. Proceedings of IEEE EUROCON 2007 The In: Proceedings of International Conference on: Computer as a tool, pp. 956–961, 2007.

[10] Generator Services Project. *http://sftweb.cern.ch/generators/*

[11] PHP: Hypertext Preprocessor. *http://sftweb.cern.ch/generators/*
[12] Scalable Vector Graphics (SVG). *http://www.w3.org/Graphics/SVG/*
[13] Faloutsos M, Faloutsos P, Faloutsos C. On Power-Law Relationships of the Internet Topology. In: ACM Computer Communication Review, Cambridge, MA, pp. 111–122, 1999.
[14] Zegura EW, Donahoo MJ, Calvert KL. A Quantitative Comparison of Graph-based Models for Internet Topology. In: IEEE/ACM Transactions on Networking, 1997.
[15] Watts DJ, Strogatz SH. Collective dynamics of 'small-world' networks. In: Nature, 12(393), pp. 440–442, 1998.
[16] Crawford JS, Waters AG. Heuristics for ATM Multicast Routing. In: Proceedings of 6th IFIP Workshop on Performance Modeling and Evaluation of ATM Networks, pp. 5/1–5/18, July 1998.
[17] Kompella VP, Pasquale J., Polyzos GC. Multicasting for Multimedia Applications. In: INFOCOM, pp. 2078–2085, 1992.
[18] Mokbel MF, El-Haweet WA, El-Derini MN. A delay constrained shortest path algorithm for multicast routing in multimedia applications. In: Proceedings of IEEE Middle East Workshop on Networking. IEEE Computer Society, 1999.
[19] Piechowiak M., Stasiak M., Zwierzykowski P. The Application of K–Shortest Path Algorithm in Multicast Routing. In: Theoretical and Applied Informatics, 21(2):69–82, 2009.
[20] Piechowiak M., Stasiak M., Zwierzykowski P. Analysis of the Influence of Group Members Arrangement on the Multicast Tree Cost. In: Proceedings of The Fifth Advanced International Conference on Telecommunications AICT 2009.
[21] Hakimi SL. Steiner's problem in graphs and its implications. Networks, 1:113–133, 1971.
[22] Royer EM, Perkins C. Multicast Ad hoc On-Demand Distance Vector (MAODV) Routing. Network Working Group, RFC: draft, July 2000.
[23] Lee S., Su W., Gerla M. On-Demand Multicast Routing Protocol (ODMRP) for Ad Hoc Networks. Network Working Group, RFC: draft, July 2000.
[24] Wang Z., Crowcroft J. QoS Routing for Supporting Resource Reservation. IEEE Journal on Selected Areas in Communications, 1996.
[25] Kou L., Markowsky G., Berman L. A fast algorithm for Steiner trees. Acta Informatica, (15):141–145, 1981.
[26] Doar M., Leslie I. How bad is naive multicast routing? IEEE INFOCOM' 1993, pp. 82–89, 1993.
[27] Vachaspathi P., Kompella JP, Polyzos GC. Multicasting for Multimedia Applications. INFOCOM, pp. 2078–2085, 1992.
[28] Dijkstra E. A note on two problems in connexion with graphs. Numerische Mathematik, 1:269–271, 1959.
[29] Piechowiak M., Zwierzykowski P., Stasiak M. Multicast Routing Algorithm for Packet Networks with the Application of the Lagrange Relaxation. Proceedings of NETWORKS 2010 – 14-th International Telecommunications Network Strategy and Planning Symposium, pp. 197–202, September 2010.
[30] Prim R. Shortest connection networks and some generalizations. Bell Systems Tech J., 36:1389–1401, 1957.
[31] Jüttner A., Szviatovszki B., Mecs I., Rajko Z. Lagrange Relaxation Based Method for the QoS Routing Problem. IEEE INFOCOM' 2001, 2001.
[32] Piechowiak M., Zwierzykowski P. Performance of Fast Multicast Algorithms in Real Networks. Proceedings of EUROCON 2007 The International Conference on: Computer as a tool, Warsaw, Poland, September 2007, pp. 956–961.