Paper

Multicast Connections in Wireless Sensor Networks with Topology Control

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Abstract—The article explores the quality of multicast trees constructed by heuristic routing algorithms in wireless sensor networks where topology control protocols operate. Network topology planning and performance analysis are crucial challenges for wire and wireless network designers. They are also involved in the research on routing algorithms, and protocols for these networks. In addition, it is worth to emphasize that the generation of realistic network topologies makes it possible to construct and study routing algorithms, protocols and traffic characteristics for WSN networks.

Keywords—multicasting, routing, wireless sensor networks.

1. Introduction

Wireless sensor networks (WSN) are communication networks composed of the several autonomous devices that use sensors to monitor physical or environmental conditions, such as temperature, vibration, pressure, stress, etc. WSN network nodes are equipped with sensors, microprocessors and transmitting and receiving devices with short-range transmit power that exchange values of measured parameters. The nodes create a global knowledge base of the examined parameters in monitored area. The user has an access to the database through one or more nodes constituting the network gateways.

Most of the problems associated with the implementation of services operating in the wireless sensor networks coincides with the challenges of all the ad hoc network. In the case of WSN networks, the energy consumption reduction by nodes becomes a priority. Devices that are members of WSN are up to miniaturized, resulting in relatively low battery capacity. Requirements for these networks relate to long lifetime. In most applications, charging or replacing batteries in such devices is impossible. The efficient use of energy resources available to sensor network nodes is one of the fundamental tasks for network designers [1]. Reduction of the energy consumed by radio communication is an important issue. Topology control mechanisms allow to maintain the lowest energy requirements of nodes and the maximum network throughput.

Due to a dynamic nature of ad hoc networks, traditional network routing protocols are not viable. Thus, nodes act both as the end system (transmitting and receiving data) and the router (allowing traffic to pass through), which results in multihop routing. Networks are *in motion*, i.e. nodes are mobile and may go out of range of other nodes in the network [2]. Nodes in these networks generate traffic to be forwarded to some other nodes (unicast) or a group of nodes (multicast) [3], [4]. Routing is then a challenging task due to the specific characteristics that distinguish wireless sensor networks from other wireless networks (i.e. mobile ad hoc networks or cellular networks).

The communication model for multicast connections provides an opportunity to reduce traffic by transmitting single packets through routers from the sender to the locations where hosts interested in receiving the data are located. Such a communication model requires special routing algorithms to be applied. These algorithms construct distribution trees (also known as multicast trees) so that packet transmission in the network can be executed.

Constrained Minimal Steiner Tree Problem (CMSTP) [5], [6] involves connecting a single source with multiple destinations in such way that one of the multiple metrics of the structure is minimal, under the restriction that the others do not violate required constraints. Therefore, when comparing different algorithms, one has to examine the costs of the multicast tree found in a given graph for given input parameters. The evaluation of the result is a non-trivial task. The metric which is to be minimized, should obviously be the lowest, but the constrained metrics may be of greater or lesser importance depending on assumed goals. The CMSTP problem can be considered both in wired and wireless networks (ad hoc, mesh, WSN, etc.).

The analysis of routing algorithms for multicast connections involves a concomitant definition of the way the network in which the algorithms are to be implemented will be represented. The problem of the appropriate representation of the network and its influence upon the efficiency and effectiveness of the algorithms under scrutiny is analyzed in [1], [7]. Reference [8] proves that in networks in which nodes are arranged and connected randomly, the effectiveness of multicast algorithms is at least twofold lower than that in hierarchical networks that reflect the properties of the internet network.

The article focuses on the quality of trees constructed by multicast routing algorithms in WSN networks that use topology control mechanisms. It starts with an overview of the available algorithms and evaluation techniques in

Section 2. Section 3 defines topology control mechanisms and basic parameters describing network topology while Section 4 contains simulation study and research methodology. In Section 5, the results of the simulation of the implemented topology control protocols along with their interpretation are described. Finally, Section 6 concludes the article.

2. Algorithms Description

2.1. Aggr_MLARAC Algorithm

The Aggregated Multi-dimensional LAgrangian Relaxation based Aggregated Cost (MLARAC) [9] is a variant of the multi-criterial unicast algorithm adopted for a multicast problem by performing an aggregation of the unicast results (paths from the source node to each of the destination nodes) into a multicast tree (a tree that spans all of the multicast group members). The MLARAC algorithm is on the other hand a multidimensional generalization of the LARAC algorithm [10].

The LARAC algorithm is a technique that utilizes Lagrangian relaxation in path optimization problem with a single constraint. The foundation of the Lagrangian relaxation is the maximization of the Lagrangian dual function. The merit of solving the Lagrangian relaxation problem is finding a maximum to a concave, piecewise linear function, which in the two criterion optimization boils down to a set of the segments of linear functions. The technique used in the LARAC algorithm boils down to finding consecutive approximations of the maximum by finding intersections of the pairs of the linear functions, which are guaranteed to intersect in the maximum neighborhood. The difficulty of finding the maximum is that the function is also piecewise linear, and thus the extreme cannot be found in the analytical way.

In the LARAC algorithm two distant segments of the function are found and based on the intersections of the lines to which they belong an approximation of the optimum is found. Based on the approximation, another segment, closer to the optimum is determined and used to find another intersection. This procedure is repeated, and after each step, a better approximation is obtained. The algorithm is guaranteed to find the optimum after finite number of steps.

The MLARAC algorithm is a generalization of the problem to multiple dimensions. Increasing the number of the optimization criteria increases the number of the dimensions of the Lagrangian dual function. In the MLARAC algorithm the intersection of lines has been replaced with the intersection of the hyperplanes. Also two problems that appear in the multidimensional space have been heuristically solved: the definition of the initial hyper-segments to intersect, and handling of the determined approximation. In the first case the one dimensional optimization is easier, because there are two sides of the hill of which the peak is to be found. There exists a robust way of selecting segments from the two sides of the hill. In the multidimensional case there is no straightforward equivalent method to determine the initial conditions. When the intersection of the hyperplanes is found presenting the new approximation of the result, there exists a condition that defines precisely, how it should be used in the consecutive intersections, but the exact equivalent for the multiple dimensions have not been found.

The aggregation of the results in the Aggregated MLARAC is performed by performing a union operation of the paths obtained from multiple MLARAC passes, from the source node to each of the destination nodes, which produces a subgraph containing all the multicast participants. Such structure is then pruned using the Prim algorithm [11]. A similar technique has been used earlier in [12].

2.2. HMCMC Algorithm

The Heuristic Multi-Constrained MultiCast (HMCMC) algorithm [13] is a relatively simple heuristic that has combines two main ideas. One is to handle the multiple criteria by aggregating them utilizing a nonlinear function:

$$m_{aggr}(t) = \max\left\{\frac{m_1(t)}{c_1}, \frac{m_2(t)}{c_2}, \dots\right\}. \qquad (1)$$

The second concept behind the HMCMC algorithm is performing the Dijkstra's algorithm multiple times [8] with the application of the metric aggregation. It defines the multicast participants as the source and the destination nodes separately. The Dijkstra's algorithm is performed from the source first, and if the shortest paths to all destinations that are obtained this way fulfill the constraints defined in the problem they are accepted as the result. Otherwise the Dijkstra's algorithm is performed from all the destinations towards which the constraints have not been met.

When relaxing the graph from the destination node towards the source node, the information from the initial algorithm pass is used to heuristically improve the quality of the selected path. Such an approach is computationaly cheap as the number of times that the Dijkstra's algorithm needs to be performed is the same as the number of the multicast participants. The experiments have shown that it also provides a feasible result in many cases.

2.3. RDP Algorithm

The RDP algorithm [14], named after the concept of the RenDezvouz Point, is an algorithm based on a simulation semantics applied a modified version of the Dijkstra's algorithm. The first of the two variations from the original algorithm is the multi-source approach. It is based on a slight change that the relaxation is initialized in multiple sources rather than one. As the result the labeling of the costs of reaching particular nodes is performed from different sources. The costs of reaching the nodes are stored separately so they don't override each other. This way if the relaxation is performed for the entire graph, the cost labels for each of the graph's nodes will store the information about reaching the given node from each of the initial nodes. If the initial nodes are the same as the multicast participants, then these cost labels may play role of a weighted routing tables for each of the graph nodes. It is worth noting that in order to deal with multiple metric the same metric aggregation is utilized as in the HMCMC algorithm.

The second variation consists in the renaming of the original Dijkstra's algorithm's operations. It is performed in such a way that instead of describing the graph relaxation a simulation of the signal propagation in the graph is described. Introducing the notion of time into the consideration presents us with a means to define simultaneously of the node analysis operations.

Combining these two variations creates a context in which it is possible to treat the relaxations performed from the different sources as concurrently performed signal propagation processes. Therefore, it is possible to state that at a certain point of the simulation time the signals propagating from all of the sources have reached a given node. In such conditions the given node is said to be equally or similarly close (in the topological metric) to all of the source nodes. The thesis behind the RDP algorithm is that such nodes (further referred to as the *rendez vouz points* or the RDPs) may be considered as the middle points for the multicast trees with a considerable probability.

In [15] two variants of the above technique have been presented and analyzed with the regard to quality of the obtained results. The quality is defined as the costs of the obtained multicast trees. The research has shown that there was no significant difference between the variants therefore the more performant algorithm should be used as the representative implementation of the general RDP technique.

3. Topology Control in Wireless Sensor Networks

Topology control is the art of controlling decision-making mechanisms of network nodes, taking into account their transmission range, that aims at a generation of networks with specific properties. Unlike the wired networks with fixed network topologies each node in wireless sensor network is capable of changing network topology by adjusting its transmission range and choosing the neighboring nodes through which data will be directed. Thus the main goal of topology control mechanism implemented in wireless sensor networks is to keep the connectivity between nodes (and therefore routing) while maintaining the lowest energy requirements of nodes and the maximum throughput of the network.

Topology control mechanisms are used to ensure that certain parameters in the whole network are secure. Decisions in nodes are made locally to achieve a global goal. Both centralized and distributed techniques of topology control can be classified as topology control mechanisms.

3.1. Network Model

The wireless sensor network can be represented by unit disc graph and consist of set of nodes distributed in a two-dimensional plane. Each sensor is equipped in omnidirectional antenna thus the transmission between nodes is possible only when they are in each other's transmission ranges (they can communicate directly) or two far away nodes can communicate through multi-hop wireless links using intermediate nodes. Such a graph is represented by an undirected, connected graph $G = (V,E)$, where V is a set of nodes and E is a set of links. The existence of the link $e = (u,v)$ between 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 communications networks). In the most common power-attenuation model, the power needed to support a link $e = (u,v)$ is $p(e) = ||u,v||^{\beta}$, where $||u,v||$ is the Euclidean distance between u and v, and β is a real constant between 2 and 5 dependent on the wireless transmission environment (path loss model) [1].

3.2. Protocols of Distributed Topology Control

A practical approach to topology control requires a creation of distributed protocols that operate locally, without the knowledge of the global state of the network, and generate topologies close to the optimal. Topology graphs should provide desirable properties of a network using symmetric edges and should be consistent (if these properties are satisfied in the graph of the maximum power that contains the edges resulting from the maximum transmit power of the nodes) [16]. It is desirable then to build a graph of the least degrees of nodes, which reduces the probability of interference in the network. It is also desirable to create optimal topology based on inaccurate information. Providing accurate information on the nodes is often too expensive, because it requires GPS receiver in each node of the network.

Topology control protocols based on the knowledge of the position of the nodes (called *location-based topology control*) are based on the assumption of available information to the nodes with a very precise location of the neighboring nodes. The easiest way to satisfy this condition is to equip the nodes with GPS receivers, which are expensive, but provide reliable and accurate information. An alternative solution is to use techniques that make an approximation of the position based on messages received from its neighbors possible. A few nodes equipped with a GPS receiver communicating with neighboring nodes may enable them to calculate position. This solution is less expensive to implement, but is associated with the generation of additional traffic on the network [17].

Local Minimum Spanning Tree (LMST) protocol calculates the local approximation of the minimum spanning tree [18]. It is performed in three, or optionally four, stages.

The first stage is the exchange of information. All nodes send messages to their visible neighbors containing their identities and locations (visible neighbor nodes that are within range when transmitting at the maximum power).

In the second stage of topology creation, each node performs locally Prim's algorithm [11] taking their Euclidean length of edge as cost – the minimum spanning tree $T_u = (VN_u, E_u)$ contains all visible neighbors of node u (VN_u) in the max-power graph $G_\varepsilon = (N, V_\varepsilon)$. Then, each node defines a set of neighbors.

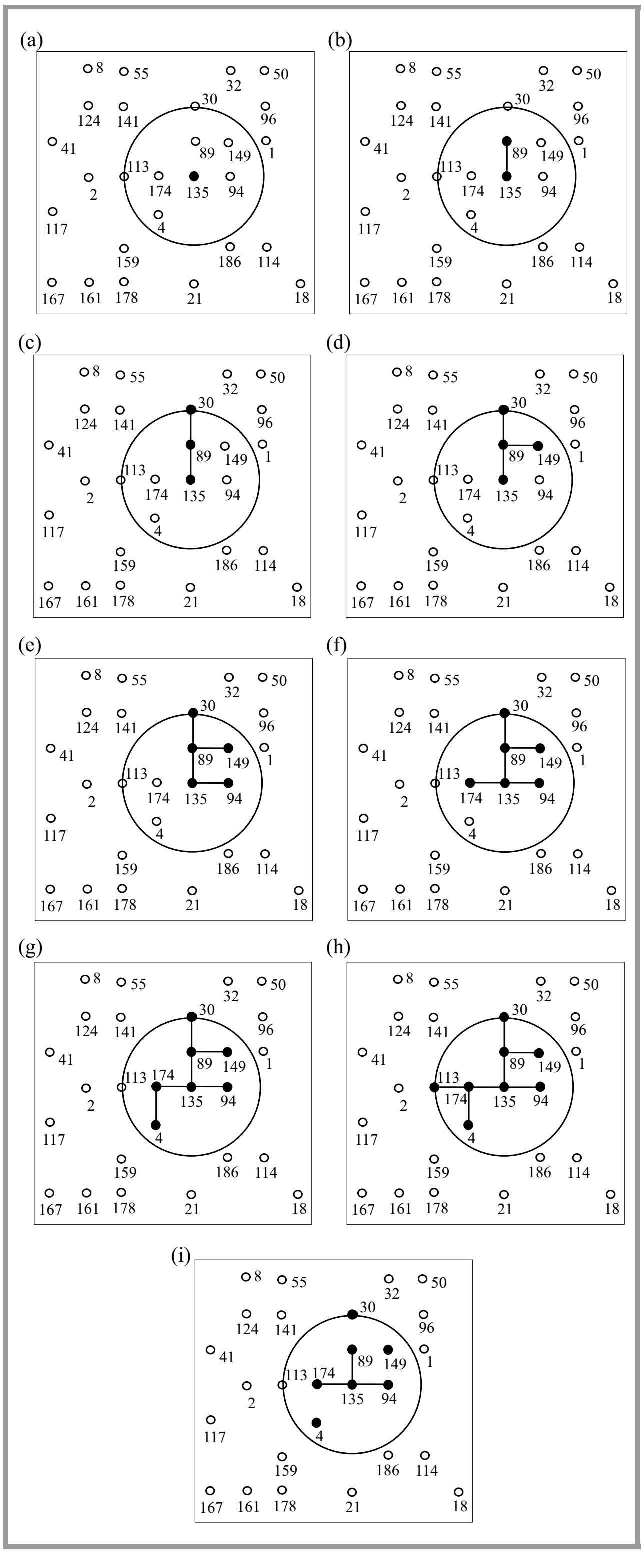

Fig. 1. The steps for generating network topology with an application of the LMST model for exemplary node deployments.

The node v is treated as a neighbor of node u ($u \rightarrow v$) if a node v is within range of node u and is available in one step in a minimum spanning tree computed in this node $T_u = (VN_u, E_u)$:

$$u \longrightarrow v \Longleftrightarrow (u,v) \in E_u. \qquad (2)$$

A set of neighbors of node u is defined as:

$$N(u) = \{v \in VN_u | u \longrightarrow v\}. \qquad (3)$$

Network topology defined in the LMST protocol is represented by a directed graph $G_{LMST} = (N, E_{LMST})$, where directed edge $(u,v) \in E_{LMST}$ exists only if $u \longrightarrow v$ (Fig. 1). In the last (required) step of the protocol, power levels of signals required for the communication with neighboring nodes are calculated. This can be obtained by measuring the power of incoming messages sent to the nodes in the first stage of protocol with the maximum power received from the visible neighbors.

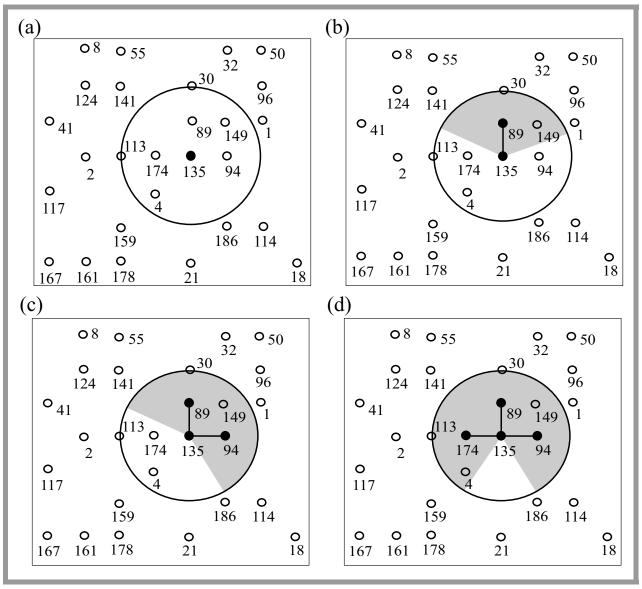

Fig. 2. The steps for generating network topology with an application of the DistRNG model for exemplary node placements.

The fourth (optional) step creates a topology with symmetric links. This is achieved either by replacing the asymmetric edges of symmetric ones or by removing asymmetric edges.

Distributed Relative Neighborhood Graphs (DistRNG) protocol [7] constructs a RNG graph built on a set of nodes N that has an edge between a pair of nodes $u, v \in N$ if and only if there is a node $w \in N$ such that:

$$\max\{\delta(u,w), \delta(v,w)\} \leq \delta(u,v). \qquad (4)$$

The DistRNG protocol uses the concept of *coverage area*. If node v is a neighbor of node u, the coverage area of node v: $Cov_u(v)$ is defined as the clipping plane with the center at node u and width $a\hat{u}b$, where a and b are the points of intersection of the circles with the radius $\delta(u,v)$ and midpoints in the nodes of u and v. The total coverage area of node u is the sum of the areas of all of its neighbors (Fig. 2).

4. Simulation Study

To support the study of routing algorithms, the topology generator for ad hoc networks has been proposed. The

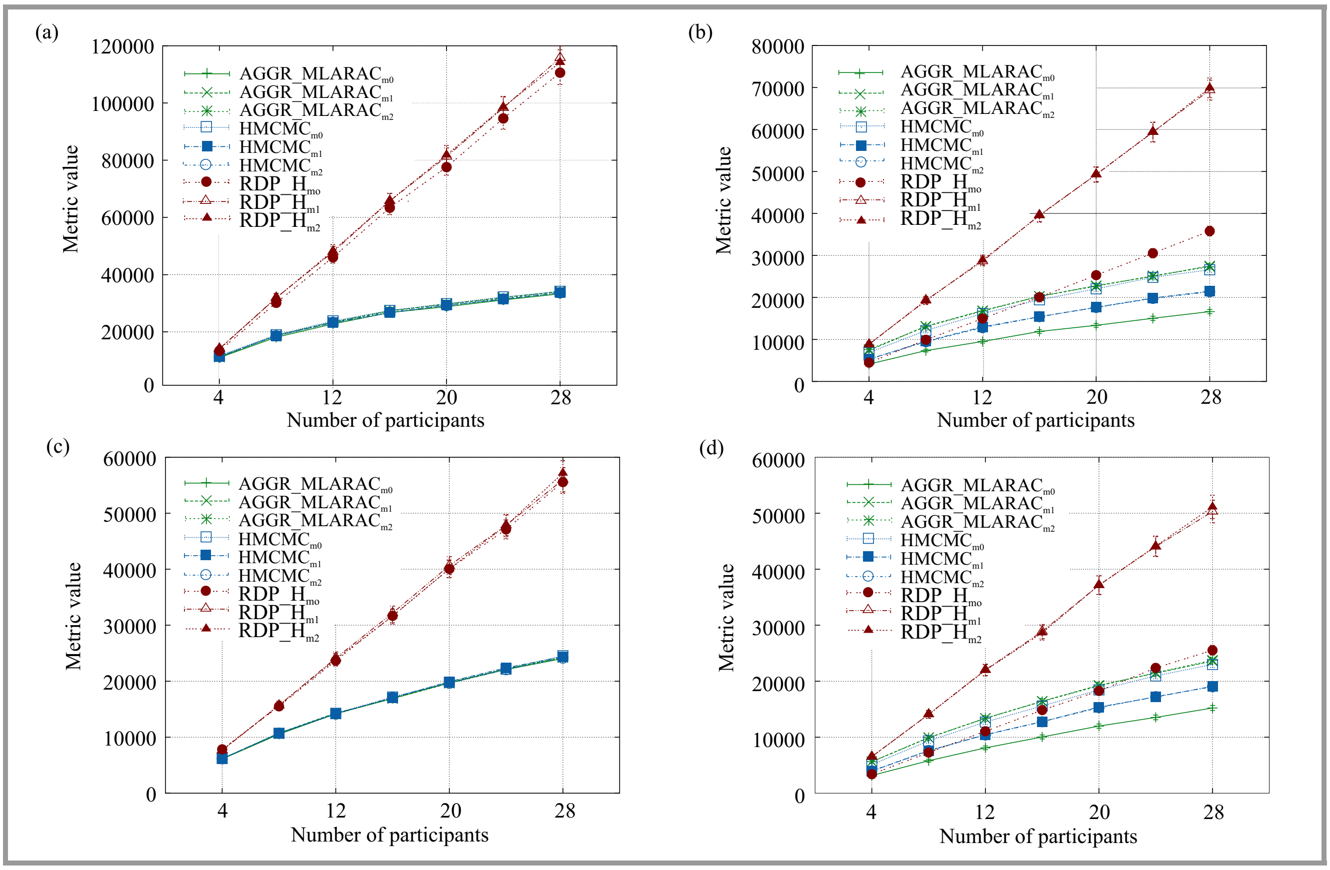

Fig. 3. Average cost of constrained multicast trees obtained in networks with 200 nodes generated according to: (a) LMST protocol, (b) DistRNG protocol, (c) Waxman model with $k = 100$, and (d) Waxman model with $k = 200$.

generator was created based on the structure and the methods that support the process of topology generation of the BRITE application [19]. Its flexibility and functionality to generate the topology of wired networks was preserved. Its capabilities were additionally extended by creating new classes supporting the process of generation of ad hoc network topologies [20].

The BRITE generator was equipped with tools needed to generate the topologies according to the two basic topology control protocols described in Section 3. Protocols based on the knowledge of the position and direction were selected. These protocols are widely used in existing ad hoc networks and their usefulness in the simulation of theoretical network models is beyond dispute. Implementation of distributed protocols is associated with a relatively high computational complexity and, consequently, with significant power requirements from the processor and memory demands from the generator. Each node in the network has limited knowledge about the entire network topology. For this reason, a creation of optimal topology is generally not possible in realistic scenarios. Hence, reflecting this problem in generative models is desirable.

During application development, additional classes extending the functionality of the generator were created. The purpose of these structures was to represent ad hoc network basis in a format determined by the BRITE application. In this way, the application was extended by additional tools that mainly supported the visualization of network topologies and the presentation of data obtained in the simulation. A comparative analysis of the most important parameters of the topology generated by the implemented method were conducted. The topologies generated by models based on the DistRNG and LMST protocols and situated in the square plane with a side length of $Size = 1000$ were compared. Nodes in all models assumed the value of the maximum transmission range of $RangeMax = 250$.

Distributed topology control protocols do not guarantee the consistency of the generated graph. Calculations of topologies diameters were performed only for nodes forming coherent graphs.

The aim of research study is to analyze the cost of the trees as a function of the number of multicast group members. The simulation process uses 1000 topologies that model ad hoc networks with LMST and DistRNG topology control mechanisms. With a constant value of the number of nodes ($n = 100$) and the maximum transmission range ($RangeMax = 250$), the LMST protocol generates network topologies with the average number of edges $k = 100$, while DistRNG – about 200.

The simulation process also uses network topologies represented by random graphs generated by the application of the Waxman method. In order to guarantee the consistency of the graph and create short edges between nodes, boundary values of the Waxman method parameters have been set up ($\alpha = 0.15$, $\beta = 0.05$). The aim of the authors was to investigate whether the results of multicast algorithms in ad-hoc networks are comparable with results obtained in random graphs with such short edges such as ad hoc networks. Therefore, they used network topologies generated by Waxman node with an average node degree of $D_{av} = 2$ ($k = 100$) and $D_{av} = 4$ ($k = 200$).

5. Experimental Results

The comparison of the multicriterial algorithms is a hard task not only because of the complexity of the algorithms themselves, but also because of the multitude of detail involved in the performance of the simulation, let alone its initiation. Thus, in [21] an innovative method of multicast algorithms evaluation based on a fuzzy system was introduced. It shows usefulness of imprecise analysis in routing algorithms comparison.

In a simulation study authors compared the cost of the multicast trees obtained in different network topologies for routing algorithms without constraint (m_0), with one constraint (m_1) and two constraints (m_2).

Simulations were performed for the sets of graphs of 200 nodes generated with LMST and DistRNG protocol, and compared with Waxman model in two scenarios: with $k = 100$ edges and $k = 200$ edges. In order to achieve the high statistical quality of the results 1000 graphs were generated for each of the topology model. Three metrics (constraints) were randomly generated from the range $\langle 1, 1000 \rangle$ for each edge in the graph. Each of the generated topologies was tested for connecting $4, 8, \ldots, 28$ multicast nodes. The technique presented in [22] was used to pick the constraints for the MCMST problem.

The results presented in Fig. 3 show a comparison of Aggr_MLARAC, HMCMC and RDP_H algorithms in relation to a number of multicast nodes m in the networks obtained with the above-mentioned methods. The results show that the average cost of multicast trees increases with the increase of the number of multicast nodes in the network, with a defined maximum delay value along the path in the tree ($\Delta = 1000$). The influence of different network topologies is observable. The costs of obtained trees are smallest in ad hoc networks with LMST protocol for each examined algorithms. Aggr_MLARAC and HMCMC multicast algorithms have the best performance in LMST ad hoc networks.

Analysis of the results presented in Fig. 3 indicate strong similarities in the results obtained with the algorithms generated network topologies using a LMST protocol and Waxman model ($k = 100$), as well as the protocol DistRNG and Waxman model ($k = 200$). In the second case, the costs of obtained trees are comparable and smallest for each examined algorithms. Aggr_MLARAC and HMCMC multicast algorithms have the best performance in DistRNG adhoc networks and networks generated with an application of Waxmax model ($k = 200$). This leads to the conclusion that in simulations studies on ad hoc networks it is possible to use fast methods that generate random graphs.

6. Conclusion

Multicriterial constrained multicast routing problems presents a non-trivial level of complexity. An additional criterion of comparing algorithms is the network topology and topology control mechanisms. Following this concept, a need for a broad analysis techniques spectrum arises.

It has been shown that exploring not only the space of the algorithms, but also the space of their comparison is worth an increased amount of effort as the conclusions may render different algorithms useful in different situations. It is also observable that for certain parameters complex network topologies obtained by the topology control protocols can be modeled by random methods. In addition, the stability of the algorithms against changes in different conditions can be shown with the use of the innovative and non-standard analysis.

The authors are still developing optimization methods for multicast connections. A new method based on innovative model of imprecise calculations called *Ordered Fuzzy Numbers* [23], [24] seems to be an interesting idea in future works.

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