Topology Properties of Ad-Hoc Networks with Topology Control

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Abstract. This article provides a detailed analysis and a description of the implementation of methods for the topology generation in ad-hoc networks with the application of topology control protocols. 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 ad-hoc networks. The article focuses on a determination of ad-hoc network parameters and discusses their influence on the properties of networks topologies. The article also proposes a new ad-hoc topology generator. 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 ad-hoc networks.

Keywords: ad-hoc networks, topology control, network topology.

1 Introduction

Ad-hoc networks are sets of nodes that form temporary networks without any additional infrastructure and no centralized control. The nodes in an ad-hoc network can represent end-user devices such as smart phones, or laptops in traditional networks. In some measurement systems nodes can represent autonomous sensors or indicators. These nodes generate traffic to be forwarded to some other nodes (unicast) or a group of nodes (multicast). 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 [1].

In some measurement systems nodes can represent autonomous sensors or indicators. Wireless networks can be used to collect sensor data for data processing for a wide range of applications, such as tensor systems, air pollution monitoring, etc. Nodes in these networks generate traffic to be forwarded to some other nodes (unicast) or a group of nodes (multicast) [2,3].

Modeling the energy consumption of nodes in ad-hoc networks is one of the most important problems faced by their designers. Ad-hoc networks are usually constructed from devices of different types. Due to their diversity, in the

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literature the emphasis is only on optimizing energy absorbed by transceivers, although it represents only 15 % to 35 % consumed energy in nodes communication using wireless cards in the 802.11 standard [4].

An analysis of topology generation and implementation methods are necessary steps in the testing process of ad-hoc network. Creation of a universal tool requires an adoption of realistic network models and design methods for topology generation that reflect characteristics of existing networks and are based on the solutions proposed in the literature.

The article discusses the basic topology control protocols for ad-hoc networks and analyzes their impact on the basic topology parameters of ad-hoc networks, such as the average node degree, diameter and edge density.

The article is divided into the following parts: Section 2 defines topology control mechanisms and basic parameters describing network topology. In Section 3, the network topology generator proposed by the authors is presented. The results of the simulation of the implemented topology control protocols along with their interpretation are described in Sect. 4. Section 5 concludes the article.

2 Topology Control

The efficient use of energy resources available to ad-hoc and sensor network nodes is one of the fundamental tasks for network designers [5]. Reduction of the energy consumed by radio communication is an important issue.

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, 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.

2.1 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) [6]. 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 [7].

LMST protocol (*Local Minimum Spanning Tree*) calculates the local approximation of the minimum spanning tree [8]. 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 [9] 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.

The node v is treated as a neighbor of node u ($u \to v$) 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 $T_u = (VN_u, E_u)$:

$$u \longrightarrow v \Longleftrightarrow (u, v) \in E_u \ . \tag{1}$$

A set of neighbors of node u is defined as:

$$N(u) = \{v \in VN_u | u \longrightarrow v\} \ . \tag{2}$$

Network topology defined in the LMST protocol is represented by a directed graph $G_{\mathrm{LMST}} = (N, E_{\mathrm{LMST}})$, where directed edge $(u, v) \in E_{\mathrm{LMST}}$ exists only if $u \longrightarrow v$.

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.

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. Figure 1 presents the steps of generating network topology with an application of the LMST model for exemplary node placements, while Fig. 2(a) shows an example topology with 75 nodes generated by the LMST protocol.

DistRNG protocol (*Distributed Relative Neighborhood Graphs*) [10] 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:

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

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

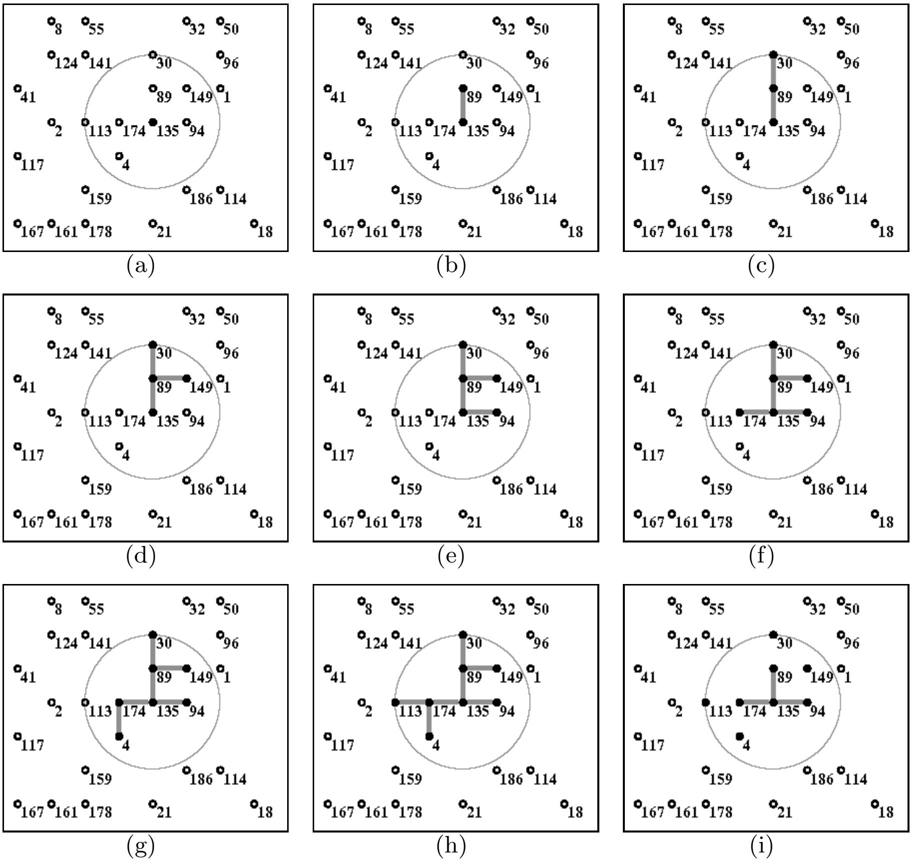
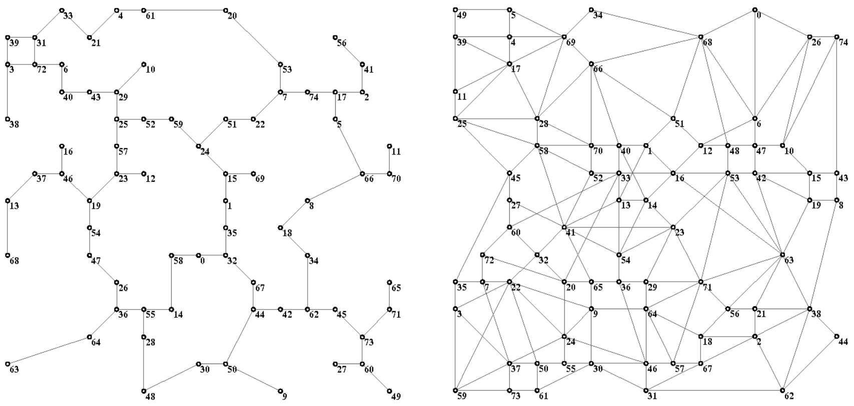


Fig. 1. The steps for generating network topology with an application of the LMST model for exemplary node deployments

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 coverage area of a neighboring node v for node u is shown in Fig. 3. The total coverage area of node u is the sum of the areas of all of its neighbors. Figure 4 presents the steps for generating network topology with an application of the DistRNG model for exemplary node placements, while Fig. 2(b) shows an example topology with 75 nodes generated by the DistRNG protocol.

2.2 Graph Model and Network Parameters

The ad-hoc network 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



(a) (b)

Fig. 2. Exemplary ad-hoc networks generated with LMST (a) and DistRNG (b) topology control methods ($n = 75$)

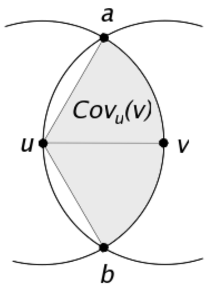


Fig. 3. The coverage area of neighboring node v for a node u

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*) [5].

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

- *average node degree* [11]:

$$D_{\text{av}} = \frac{2k}{n} \tag{3}$$

  where n – number of nodes, k – number of links,
- *hop-diameter* [11] – the length of the longest shortest path between any two nodes; the shortest paths are computed using *hop count* metric,

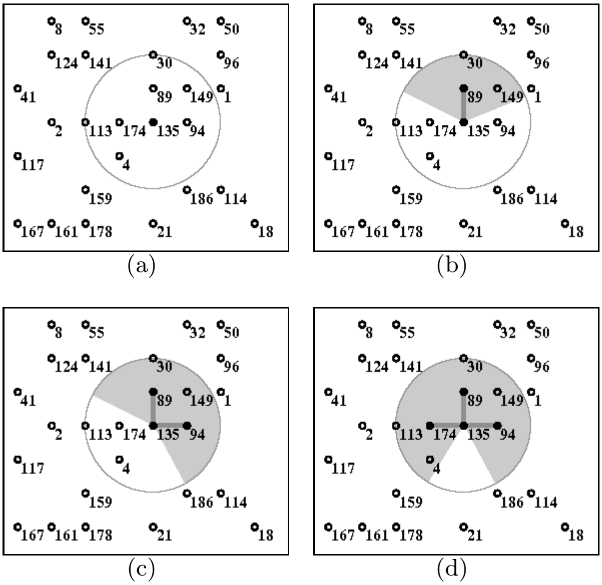


Fig. 4. The steps for generating network topology with an application of the DistRNG model for exemplary node placements

– *edge density*:

$$ED = \frac{k}{E_{\max}} \tag{4}$$

where $E_{\max} = \frac{n(n-1)}{2}$ is the maximum number of edges in fully connected graph with n nodes.

3 Network Topology Generator

The topology generator for ad-hoc networks was created based on the structure and the methods that support the process of topology generation of the BRITE application [12]. 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 [13].

The BRITE generator was equipped with tools needed to generate the topologies according to the two basic topology control protocols described in Sect. 2. 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.

Java classes used to generate the topology of ad-hoc networks (*DistRNG*, *LMST* and *KNeigh*) are derived from *AdhocModel* class that, just as *ASModel* and *RouterModel* classes, is derived from the abstract *Model* class [12]. The *AdhocModel* class stores the values of the variables used by all models of ad-hoc networks generation – *RangeMax*, *bwMin*, *bwMax*, *bwSpread* and provides a method of *PlaceNodes* responsible for the deployment of nodes within the plane as well as *AssignBW* that assigns metrics to edges in the final stage of topology generation. The *PlaceNodes* method was taken from the classes created for the generation of router-level and autonomous systems topologies. Nodes were deployed with a normal distribution, though the choice of heavy-tail distribution was omitted.

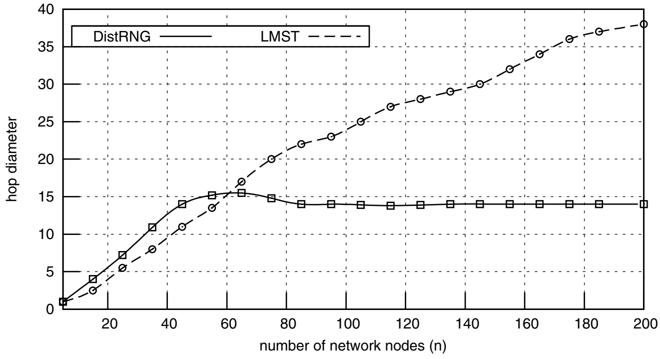
The *AssignBW* method, responsible for the imposition of attributes on the edges, was changed. In wireless networks there are other factors affecting the bandwidth and latency as compared to wired networks. The bandwidth of the link does not depend on the type of transmission medium, that is the same throughout the network, but on its length instead.

The bandwidth in generated ad-hoc networks is first allocated on the basis of the input parameter $bwMin$ and $bwMax$ using a linear function that assigns a specific minimum bandwidth to edges of length equal to the radio range of the source node and the maximum bandwidth to edges with a length of 0. Randomness, that can partly compensate for inaccuracies of generative methods resulting from the adoption of a very simple model of propagation, is ensured by the implementation of the *bwSpread* parameter introducing random scattering of bandwidth *bw*. It is obtained by a linear function within the range $[bw \cdot (1 - bwSpread), bw \cdot (1 + bwSpread)]$.

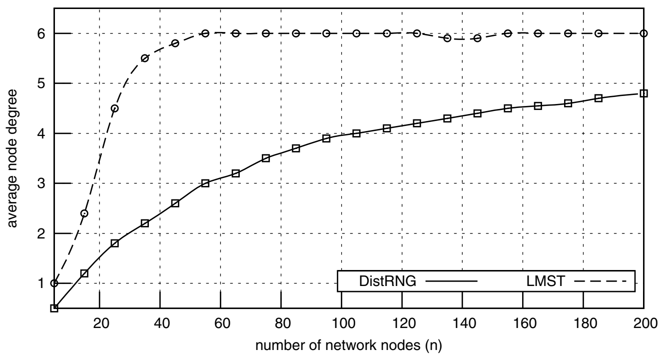
4 Simulation Results

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 $Size = 50$ were compared. Nodes in all models assumed the value of the maximum transmission range of $RangeMax = 10$.

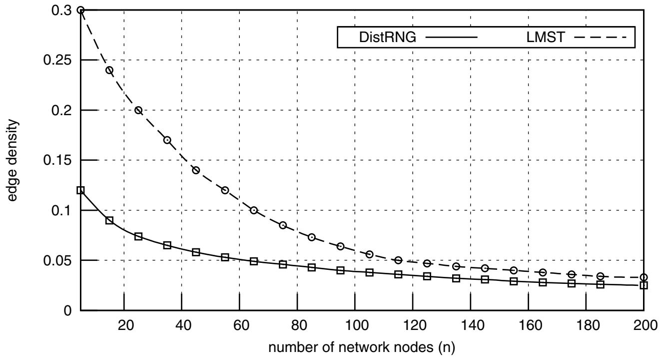
Distributed topology control protocols do not guarantee the consistency of the generated graph. Calculations of topologies diameters were performed only for nodes forming coherent graphs.



(a)



(b)



(c)

Fig. 5. Hop-diameter (a), average node degree (b) and edge density (c) versus to the number of network nodes

Hop-diameter determines the maximum number of hops in the transmission along the shortest path between any pair of nodes in the network. Its value is important, the broadcast traffic, among others. A low value of the hop-diameter has an impact on a reduction of the level of traffic on the network. The theoretical value of hop-diameter tends to infinity. In realistic scenarios, however, the density of nodes within the plane is limited and depends on the maximum number of nodes that can be deployed in a given area.

The lowest values of the hop-diameter parameter are observable in the networks generated with an application of the DistRNG protocol, whereas the highest values were obtained in the LMST protocol. The DistRNG protocol stood out offering a faster stability of this parameter (constant values were obtained for a smaller number of network nodes).

The average node degree (D_{av}) in the graph allows the level of interference in the network to be estimated [14]. The higher the average degree of logical nodes in the graph, the greater the probability of interfering transmissions. The networks generated with the LMST protocol are characterized by higher values of the average node degree. In the networks above 50 nodes, the value is fixed at 6.

The limitation of the range of nodes makes the edge density values low regardless of the density of nodes. The lowest values of this parameter are observable for the topologies generated with the application of the DistRNG protocol (Fig. 5(c)).

The analysis of the results shows that the best performance is achieved by using the generation model based on the DistRNG protocol. The choice of the generative method must also take into account the technological capacity to implement them.

5 Conclusions

The article discusses the basic topology control protocols for ad-hoc networks and analyzes their impact on the basic parameters of ad-hoc networks. The results show a significant influence of adopted topology control protocol on the parameters of ad-hoc network topology. The authors believe that the variation of the results will have an impact on the efficiency of unicast and multicast routing algorithms[1].

The article also presents an original topology generator of ad-hoc networks. The proposed topology generator is an indispensable tool for researchers and designers of ad-hoc networks that allows ad-hoc topology features to be simulated and analyzed. Further, it makes it possible to improve the process of designing and testing routing protocols dedicated particularly for ad-hoc networks.

The conducted research presented in the article will be used by the authors in the routing algorithms evaluation. Further investigations will include a greater number of network parameters (i.e., the clustering coefficient) and parameters directly related to the routing algorithms (both unicast and multicast).

[1] In earlier works [15], the authors showed the influence of the average node degree on the cost of trees constructed by multicast routing algorithms.

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