
Topology Properties of Ad-Hoc Networks

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Summary. 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). The article focuses on the network parameters determining and their influence on ad-hoc networks properties. It also proposes a new approach in ad-hoc networks modelling.

1 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* [2]. 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 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 [6, 7]. 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 propagation model. Chapter 3 presents simulation study regarding authors' ad-hoc topology generator. Chapter 4 presents simulation results. The final chapter sums up the discussion.

2 Network Model

2.1 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.

2.2 Propagation Model

Ad-hoc network topologies are analyzed in many works, including [3] and [4]. 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:

$$P_r \sim \frac{P_s}{d^\alpha}, \quad (1)$$

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 $\alpha \in (2, 6)$ [4]. 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 [4] and [3]. 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 [5].

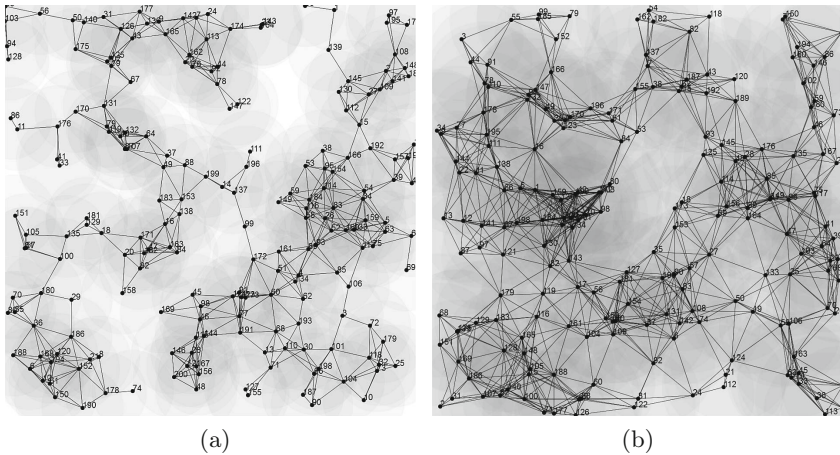


Fig. 1 Visualization of ad-hoc networks with 200 nodes obtained using the proposed generator for $r = 100$ units (a) and $r = 150$ units (b)

2.3 Network Parameters

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

- *average node degree* [6]:

$$D_{av} = \frac{2k}{n} \quad (2)$$

where n – number of nodes, k – number of links,

- *hop diameter* [6] – 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 [14].

Let $\Gamma(v)$ be a neighborhood of a vertex v consisting of the vertices adjacent to v (not including v itself). More precisely:

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

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 [1, 12]:

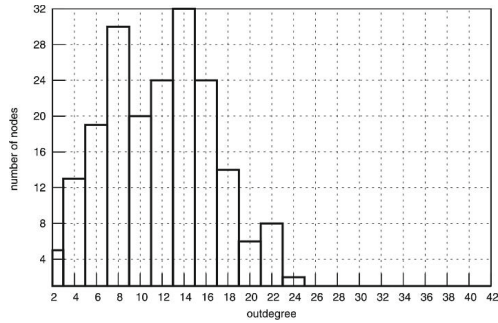
$$\hat{\gamma} = \frac{1}{|V| - |V^{(1)}|} \sum_{v \in V \setminus V^{(1)}} \gamma_v. \quad (4)$$

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.

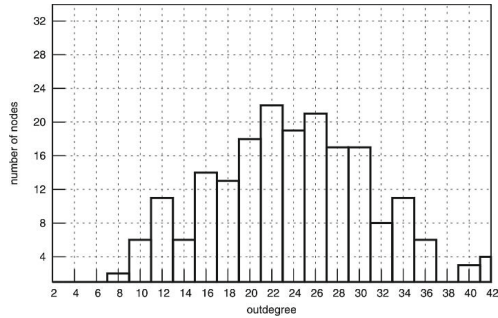
3 Simulation Study

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 [10] and SVG [11] 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.



(a)



(b)

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

Network topologies are prepared with a pseudorandom two dimensional uniform distribution generator (LCG) [9]. 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 1a and 1b 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.

4 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

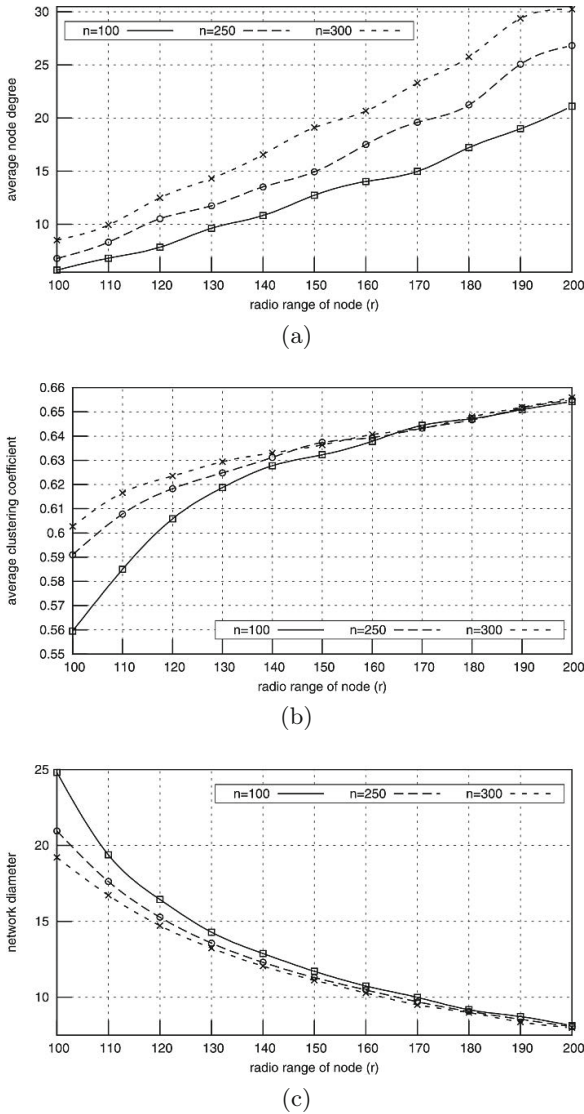


Fig. 3 Average node degree (a), average clustering coefficient (b) and network diameter (c) versus to the radio range of node (r)

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. 3a) 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. 3b). 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. 3c). Hop-diameter value is biggest for $n = 100$ and $r = 100$ (small networks with small radio ranges).

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.

5 Conclusions and Future Work

The article defines representative network parameters as average node degree, clustering coefficient and diameter, and 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 [7, 8]. There is a need to confirm these tendencies in ad-hoc networks.

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.

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