# Performance analysis of scale-free communities in ad hoc networks

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# Performance analysis of scale-free communities in ad hoc networks

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***Abstract*—The underlying user's social network plays the most significant part in the distribution of the end-to-end traffic in the ad hoc network. In this paper we propose a new model for a user social network based on the scale-free phenomenon and small-world clustering effect that can be found in the real social networks. The proposed model is then used for creation of new traffic and physical movement models in order to investigate the performances of the ad hoc network. The results point out that the expected network performances can be much higher than the ones evaluated using simple random movement and traffic generators.**

***Index Terms*— ad hoc networks, communities, performances, scale free and small world phenomena.**

## I. Introduction

THE field of ad hoc networks continues to be one of the most popular and challenging fields when talking about communication networks. The inexpensive and widely available wireless equipment have brought the ad hoc networks closer to the end user and the ever expanding list of possible applications attracts even more attention.

Ad hoc networks provide wireless connectivity with freedom of movement that goes beyond the limits of the conventional wireless network based on the access point infrastructure. The ad hoc network is a network that consists of wireless mobile users only and it does not rely on any backbone infrastructure or special pre-use interventions. The mobile nodes are free to move around as long as they do not go out of the range of the network. In order to provide full interconnectivity the nodes have two different roles. Firstly, they can be either source or destination for the transferring data. Secondly, they may need to become routers for some other data source-destination stream for situations wherein the source and the destination are not in the radio range proximity. The ability for users that are not in radio range to exchange data and information is provided via so called multihop paths over one or several intermediate nodes that forward the data toward the destination.

The absence of infrastructure and on-the-fly establishment are the major reasons for the enormous number of applications for ad hoc networks [1]. The possibilities start from the military on the battle field for instant soldier linking, over rescue missions or exploration teams for anywhere, anytime connectivity, towards today's favorite ad hoc campaign headquarters and everywhere business meetings.

The common thread of all of these application themes is the human factor that uses the ad hoc network for information sharing [2]. This aspiration for means of sending information from one user to the other directly affects the data flow in the underlying ad hoc network. The ad hoc network provides means for user communication and it's infrastructureless, wireless, mobile aspects allows the users not to take into consideration the communication medium, but just use it in any way they feel necessary.

Thus, when analyzing the performances of ad hoc networks that are used to provide means for information sharing for groups of users, care must be taken that a proper model of the end-to-end communication is used. The way the end-to-end connections are going to develop falls under the rules of the relationships between the users of the network. This means that the traffic pattern can be extracted from the graph that models the user interconnection, that is, from the social network that is created by the users of the ad hoc network.

In the past decade there have been several major findings that grasp the modeling and properties of social networks. The biggest impact is the emergency of the small-world effect [3] and the scale-free property [4] found in every social network. The aim of the small-world effect is to emphasize the natural grouping into communities that is present in every social network, while the aim of the scale-free property is to create a situation for emergence of the rich-getting-richer phenomenon that models the tendency for a small number of individuals to have a surprisingly high connectivity [5].

In order to bring the ad hoc communication modeling closer to a real-life situation by the means of using the underlying social network of ad hoc users, we developed a complex network model that captures the small-world and the scale-free phenomena in a way that the graph that corresponds to the user interaction is a blend of scale-free communities.

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When analyzing an ad hoc network, the traffic communication pattern is only one point where care must be taken that the modeling is suitably done. The wireless aspect of the network means freedom for node movement, which on the other hand is known to have great impact on the network performances [6]. Furthermore, if we consider the social aspects of the ad hoc network users, we naturally expect the users to have a pattern of movement that will correspond to their social interconnections, that is, users that belong to the same community are expected to be in physical proximity of each other. In order to reflect this sort of behavior in our ad hoc network modeling, instead of standard random direction mobility generators, we made a modification of the community movement generator given by [7] in a way that allows us to simulate the movements of the scale-free communities obtained with our model.

The remainder of this paper is organized as follows. The second section brings forth complex networks and the way we decided to model them using the scale-free communities (S-FC) model. Section 3 illustrates the integration of this model in our simulation scenarios for ad hoc network. In Section 4 the results of our performance investigation are presented. Finally, the last section concludes the paper.

## II. Complex Networks

During the past decade, the emerging "science of networks" [8] is continuously gaining attention from the scientific communities of various disciplines: social and natural, formal and applied; showing that results obtained from one field are easily applicable in almost every other. This relationship is ever deepening as new examples that show the ubiquitous characteristics of networks come to light [9]. Social networks, the Internet, the WWW, the power supply networks, and many others, all posses the small world and scale-free properties [8].

The small world phenomena [9] emphasizes the existence of groups or clusters in the network wherein the nodes are tightly connected to each other while the network is holding by a number of inter-clusters links. This implies that the network has a large clustering coefficient (high local density), but also a small average path length (low global separation). That means that although the nodes tend to group, the inter-groups links create paths of just a few intermediate nodes to any destination in the network (e.g., the largest social network, i.e. mankind, has average path length of 5.8, the basis for the famous "six degrees of separation" statement). The small-world phenomenon is successfully captured using the Watts and Strogatz model [3]. However, the resulting network has a uniform distribution of the node degree.

On the other hand, the scale-free phenomenon [10] is mainly concerned with the node degree distribution in the network. Scale-free networks have a power law node degree distribution, that is, when the node degree is plotted on a double logarithmic scale, a power law appears as a straight line with a negative slope ( $p(x) = Ax^{-\alpha}$ where for most of the observed networks $1 \le \alpha \le 3.5$ ). This implies that there are a large number of nodes in the network with a few links, while a small number of nodes (known as hubs) have a great number of links and keep the network together. The work of Barabasi and Albert [10] has lead to many scale-free models that usually introduce random preferential attachment mechanism and allow generation of a network with a power law distribution and a small average path length.

Using these findings of the theory of complex networks, we can create models that can be used to depict the physical connections between network devices, the routing of the data packets in a communication network, or the end-to-end communication between the network users.

The impact of the small world phenomenon on the performances of ad hoc networks is observed in [11], while in [12] the influence of node's mobility in clustered ad hoc network is shown. The scale-free property and ad hoc network performances are investigated in [13], while a hybrid variation is presented in [14]. In this paper an attempt to merge these individual results into a one comprehensive approach is made.

The main goal of this paper is to present a model that will realistically capture the social network of the ad hoc network users and, using this model, create a traffic and movement generator that will mimic the way the ad hoc network is going to be used by its users in a real life situation. The model should incorporate both the small world and the scale free properties which are constantly observed in the real social networks.

The existing models that incorporate these phenomena fail to create a model of a network that can be partitioned in a desired number of communities. In most of the cases, the obtained network has a strong power-law property and can not be partitioned into clusters at all. In other cases, the partitioning can be achieved, but all, or a great portion, of the hubs are belonging to the same group, which is an inadequate representation of the real life situations wherein each group has at least one 'group leader' that is represented as a hub in the network. Our goal was to create a network which will follow the power-law node degree distribution, but will be easily partitioned into groups, i.e. communities.

In our S-FC model the small world phenomenon and the scale-free property are incorporated in a manner that the obtained network is created as a network of a given number of clusters, i.e. communities, which have a scale-free property and are afterwards interconnected in a way that allows for the network as a whole to maintain the scale-free property. The input parameters for the model are:

1. number of nodes - *N*
2. number of communities (groups) - *G*
3. levels of intercommunity interaction:
   a. number of originating hubs – *OH* and
   b. number of destination hubs - *DH*
4. probability for intercommunity interaction - *pH*

According to the S-FC algorithm, the network is generated as follows:

1. Using the Barabasi-Albert model based on

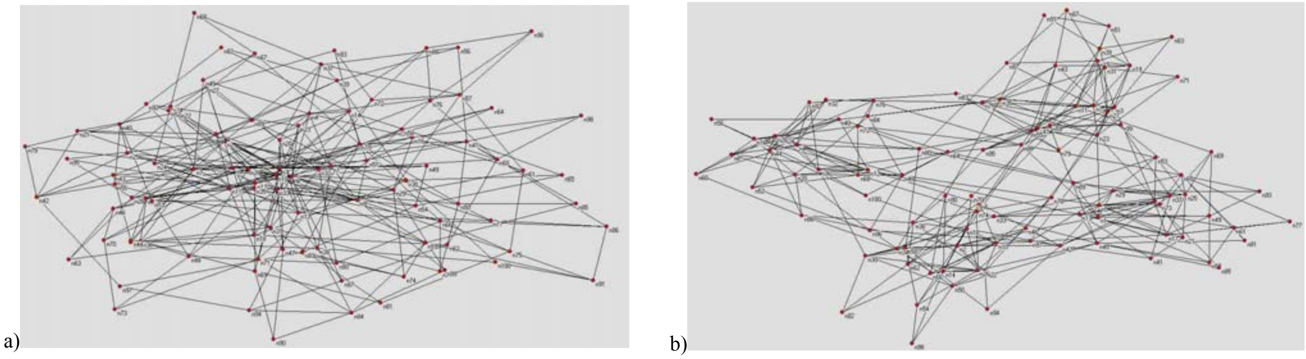


Fig. 1. Networks obtained using the SFcommunity model for $N$ = 100 nodes and $n_0$ = 3, $OH$ = $DH$ = 2, $pH$ = 0.5 and number of communities $G$ = 1 (a) and 4 (b)

preferential attachment, generate G independent scale-free groups with a total number of members equal to $N$.

a. Start from a full mesh core of $n_0$ nodes,
b. Add a new node with $n_0$ links to existing nodes. The nodes to which the new node will be linked are chosen using preferential attachment according to which the probability to attach to node $i$ is $p_i = D_i \Big/ \sum_j D_j$ , where $D_i$ is the $i$-th node degree,
c. Repeat the previous step until the desired group size is reached.

2. The $G$ scale-free networks are interconnected using the $OH$ , $DH$ and $pH$ parameters as follows:
   a. Using preferential attachment choose $OH$ nodes from each group,
   b. With probability $pH$ chose to connect each of the chosen $OH$ nodes with $DH$ nodes from every other group using preferential attachment again.

Step two of the model is responsible for creating a complete connected network by interconnecting the separately created groups. The use of preferential attachment in this step secures that the interconnections between the communities will be done among the local hubs, thus maintaining the power-law node degree distribution of the overall network. The feature of hub-to-hub interconnections, which is observed in many real networks, is also preserved.

Fig. 1 illustrates the obtained networks with 100 nodes using the S-FC algorithm where the scale-free network with 4 communities (Fig. 1.b) can be compared to a standard scale-free network (Fig. 1.a). Please note that for the case for one community the obtained network is the same as it would have been obtained using the Barabasi-Albert scale-free model.

The properties of the networks obtained using our S-FC model have been evaluated and tested according to [15]. The results from the Kolmogorov-Smirnov tests for goodness-of-fit to the power-law distribution have shown that the node degree distribution in the network follows the power-law distribution as long as the number of members in the communities is not too small (one community should have at least 15 nodes). For our case study we used networks with sizes of 100 nodes for which as long as the number of communities is not higher than 6 we maintain the power law node degree distribution.

In Table I the values of the key network properties for 4 communities compared to a standard scale-free network are given: the alpha coefficient of the power law distribution, the clustering coefficient and average path length of the network, as well as the S-metrics [16] that reflects the amount of hub-to-hub interconnections. Higher values of the $OH$ and $DH$ parameters result into merging of the communities. Table I shows that the obtained network have an alpha coefficient, clustering coefficient and average path length that are consistent with the characteristic values that have been found for many observed social and other types of networks.

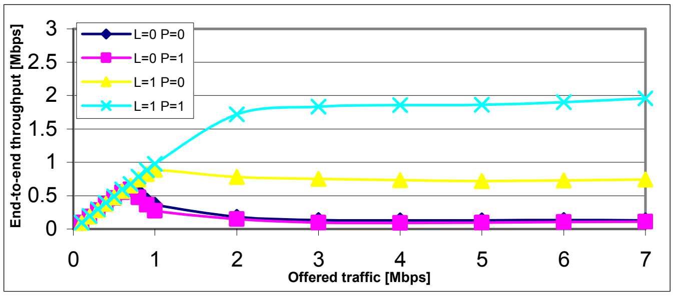
TABLE I
PROPERTIES OF SCALE-FREE-COMMUNITIES NETWORKS
*WITH* $N$=100 $N_0$=3 $PH$=0.5

| No. of communities | OH | DH | Alpha | Clustering coefficient | Average path length | S metrics |
|---|---|---|---|---|---|---|
| 1 | / | / | 2.4 | 0.071 | 2.746 | 0.509 |
| 4 | 1 | 1 | 2.83 | 0.256 | 3.624 | 0.435 |
| 4 | 1 | 2 | 3.0 | 0.233 | 3.277 | 0.423 |
| 4 | 2 | 1 | 3.0 | 0.233 | 3.338 | 0.42 |
| 4 | 2 | 2 | 3.2 | 0.169 | 2.917 | 0.403 |

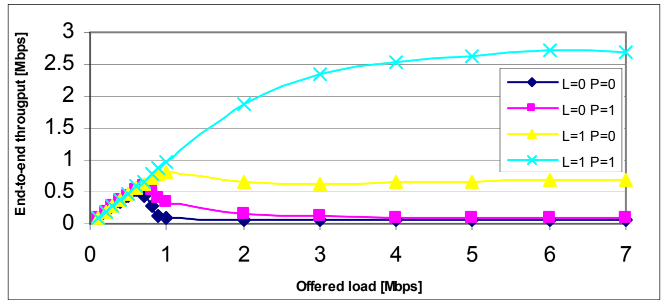
## III. SCALE-FREE COMMUNITIES APPLICATION LAYER AND SIMULATION SCENARIOS MODELING

In order to realistically simulate the conditions under which an ad hoc network would be used in real life situations as a means for information sharing between groups of humans, we used our S-FC model in combination with a specialized custom made application layer for the widely used open source NS-2 network simulator [16].

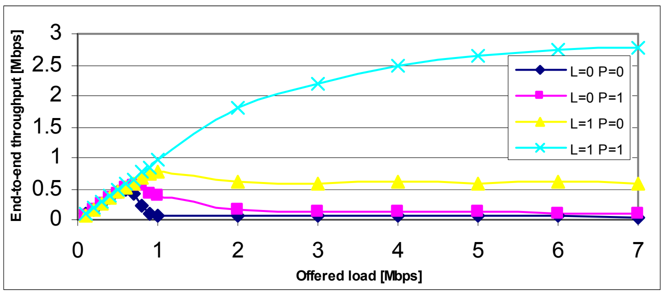
Our custom application layer uses the information read in from the generated social network using the S-FC algorithm. The obtained network defines the relationships between the ad hoc network users and their need for communication. In this way we define the social links (information links) for each node in the ad hoc network. We simulate each node of the ad hoc network as a different node of the S-FC network with its given links to other participants in the ad hoc network. Each node is allowed to communicate only with its defined information links (in this way we let the node send and receive data information only from its known 'friends').



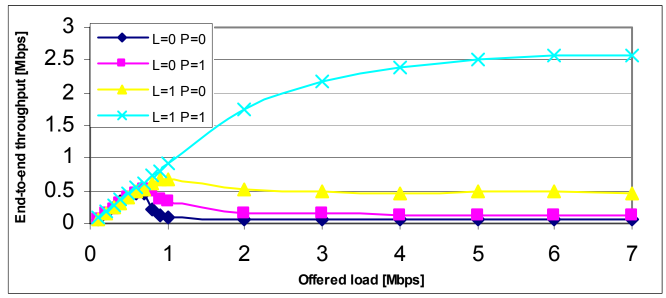

a) static nodes




b) nodes moving with speed of 1 m/s




c) nodes moving with speed of 2 m/s




d) nodes moving with speed of 5 m/s

Fig. 2. End-to-end throughput for ad hoc networks that incorporate the S-FC traffic and/or movement patterns for different node speeds

Whenever a node sends a new message using this application layer, the node randomly chooses a destination from the pool of known information links. In addition to the custom application layer we created a traffic generator that generates traffic with a given offered load over the simulation time.

We also created another tool that serves as a mobility scenario generator which is a modified version of the community mobility generator [18]. The generator is modified so that it reads in the generated S-FC network and than assigns proportional parts of the simulation area to each community. The nodes are uniformly scattered in the appropriate community area. During the simulation the nodes are moving according to the random direction model in the boundaries of their respective community.

We conducted several series of simulations in order to investigate the ad hoc network performances of our scale-free communities. The simulations were performed on the SeeGrid infrastructure. In our scenarios we observe the total end-to-end throughput in the ad hoc network (total received data bits per second in the whole network) while varying the offered load from 0.1 Mbps up to 7 Mbps.

The ad hoc network consists of 100 nodes that are uniformly distributed in a square area of 1 $km^2$. The nodes are equipped with radios that use the IEEE 802.11 protocol, while the multihop routing is provided using the AODV routing protocol [19], and on the transport level we use UDP. We were studying the ad hoc network for several different cases of node mobility for our movement generator: static nodes, nodes with average speed of 1 m/s, 2 m/s and 5 m/s. We decided to observe the performances of a S-FC network with 4 communities and clustering coefficient and average path length that are closest to the ones obtained for a standard scale-free network which is due to the greatest number of links in the network (no. of originating hubs *OH* = no. of destination hubs *DH* = 2).

The simulation scenarios also offer the possibility to use the created S-FC social (information) network only on the logical (application) layer L=1, while the nodes are scattered and moving randomly in the complete simulation area; or only on the physical layer P=1 in which case the nodes are moving together within their communities, but the communication is completely random; or on both, physical and logical layers L=1 P=1 wherein the communication and the movement pattern are according to the S-FC modeling.

## IV. Performance Analysis

We analyze the behavior of the ad hoc network when using the S-FC application layer and mobility generator for different node speed and different offered network traffic load. Our aim is to investigate how much the S-FC traffic and mobility modeling affect the end-to-end throughput of the ad hoc network. Fig. 2 depicts the ad hoc network performances for various node speeds and use of the S-FC network model.

It is interesting to note that when using the S-FC based node movement patterns only (L=0 P=1) there is a very insignificant rise of the network performances when compared to the other cases when the traffic is created using the S-FC based application layer (L=1). Another interesting result are the performances for the L=1 P=0 case. The results show that even in cases when the physical positioning of the nodes is not restricted to any community the ad hoc network performances are increasing. This is because of the lesser need for different path routes through the network since the network users have specific destinations-friends, thus lowering the number of route discovery packets.

As it is expected the best performances are obtained when

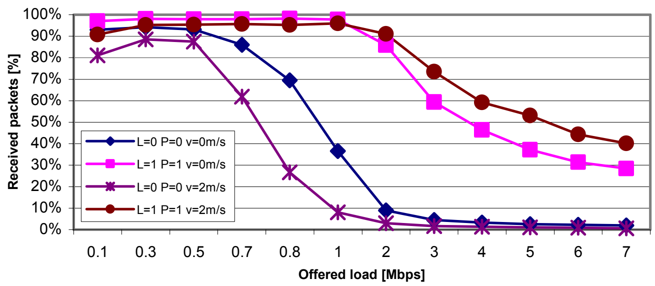



Fig. 3. Received to send packets ratio for pure random and S-FC modeled ad hoc networks with static and mobile nodes

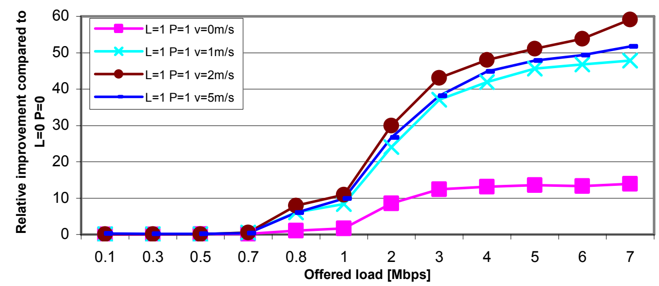



Fig. 4. Relative improvement of the network performances when using the S-FC model for different node speeds

the S-FC network model is used on both logical and physical layers (L=1 P=1). This case is also the one that is to be expected to be found in real-life ad hoc network deployments. This means that the scenarios with pure random traffic and movement generators may be misleading on the estimates of the ad hoc network performances in practical situations.

Also, it can be seen that the performances of the static scenario are somewhat lower compared even to the moderate node speed. This is due to the problem of constant lengthy routing paths for the static case. For higher network loads it becomes increasingly difficult to send data over longer routes because of the intense contention for the shared medium. When the nodes are mobile, the routes are changing (however these are not dramatic changes since the nodes of the same community stay in one to two hops proximity) thus allowing for nodes from different communities to exchange packets over shorter routes at given times when they move closer together.

The percentage of received packets for static and mobile nodes for the random scenario and the scenario wherein the traffic and mobility pattern are modeled according to the underlying S-FC network are shown on Fig. 3. It is evident that, especially for the high network loads, the performances of the S-FC scenarios are overwhelmingly increased providing much higher network utilization. The ad hoc network is relieved of a great number of routing packets and thus free to transport much more data packets. The performances for 1-3 Mbps offered load show that the ad hoc network can cope with moderate network load a lot better that it is at first expected.

On Fig. 4 the overall improvement in the network end-to-end throughput relative to the pure random scenario [(L=1 P=1 end-to-end throughput) – (L=0 P=0 end-to-end throughput)] / (L=0 P=0 end-to-end throughput) is shown for different node speeds. The results show that the performances, especially for higher load, increase up to tremendous 60 times. The improvements are starting to be evidently higher for network loads higher than 0.5 Mbps and are rapidly rising. The relative improvement is lowest for the static case, reaching 14 times relative improvement.

## V. Conclusion

In this paper we present a new scale-free communities algorithm for complex network modeling that incorporates the small-world and scale-free phenomena. Using this network model we attempt to create more realistic traffic and mobility models for ad hoc networks. The analysis of the obtained results have shown that the ad hoc network performances in situations that closely resemble the real life ad hoc network users interactions are to be much higher than the ones forecasted using random scenarios especially for higher network loads.

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