Impact of Community Structures on Ad Hoc Networks Performances

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Abstract. In this paper the impact of node communities on the ad hoc network performances is investigated. The community structures are viewed on the logical (application) level and on the physical level. They are modeled using complex network theory with which socially based mobility and communication patterns are developed. The different approaches in modeling offer the view of how the distribution of interconnections between the nodes influences the network performances. The results show that the logical interconnections have a great impact on the network performances especially in the cases when the node degree distribution follows the scale-free law.

Keywords: communities, ad hoc network, performances, complex networks, logical and physical level.

1 Introduction

The wireless fidelity of today's small and affordable devices have risen the massive need for instant and effortless networking on a whole new level that can not be satisfied with the usual access point configurations. What is expected from wireless devices today is the very definition of ad hoc networking: the ability to form a wireless mobile network anytime, anywhere without the use of any centralized administration or existing infrastructure [1].

Ad hoc networks offer this effortless networking by employing a special routing protocol that treats every device as end-node and a router at the same time. In this way the nodes act benevolently forwarding packets from other sources towards their destinations. This behavior allows for two nodes that are not in their radio range to communicate via their intermediate neighbor nodes forming so-called multihop paths.

However, the idea of creating an instant network as means for sharing information has influences on both, the networking protocols and the mobility and communication patterns. This means that as the need for the anytime, anywhere network establishing dictates the use of special ad hoc routing protocols, the same need of people to share information shapes the topology of the network as well as the traffic on the application level in the network.

The people that want to use the ad hoc network as a means for information sharing are part of an underlying social network that depicts the way people are interconnected. The connections in the social network show the way people communicate by indicating the friendships and communities of friends with stronger ties inside the community. When we apply communication via ad hoc network over this social layout, it is normally expected that the network users will continue to honor the social ties and merely use a technological way to share the information between friends [2].

Thus, while we strive to tweak the ad hoc network performances so they can satisfy the need for higher throughput, it is essential that we model the network deployment using appropriate techniques. This means that while we investigate the network behavior, we must use communication and mobility models that will produce data and movement patterns that will reflect the social life of the network users.

In the light of this approach, we use the complex network theory in order to create a social model of the network users which will afterwards be used as an underlying basis for creating communication patterns and mobility scenarios in the network. When creating a model of a social network, there are few interesting characteristics that must be taken into account. It has been shown that all social networks which are part of the complex network family show certain global and local features that they have in common. This is the reason why complex network theory abandoned the social network modeling using the random graphs proposed by Erdos and Renyi, and moved on to the discoveries of the last decade which led to the small-world and scale-free properties.

We used the small-world and scale-free phenomena for modeling a socially based communication pattern for ad hoc networks and we investigated the impact this modeling had on the ad hoc network performances. The results presented in [3] and [4] show that the ad hoc network performances greatly differ when compared to the traditional way of modeling using a random communication pattern. This implies that the results obtained for the network performances behavior when investigating some special network aspects can be misleading. For example, the authors in [5] are investigating the performances of ad hoc networks that use different routing protocols on the basis of complete random traffic and random movement, which as we argued previously does not represent the real life deployment of the network. Similarly, in [6] the impact of coverage on the network performances in investigated using random models, but again this is under great influence of the social aspect of the network. In [7] performances of ad hoc networks using directional beams with group mobility are presented, and while the results include the physical aspects of social grouping, they also lack the application modeling of social information sharing.

However, one other characteristic of social networks is the natural community forming that occurs in the network. Social network exhibit the occurrence of a number of communities in the network that point the groups of friends that establish closer relationships inside their group while scarcely communicating outside the group via a small number of intergroup links. This forming of groups influences not only the communication pattern of having intense traffic inside the groups and lower amount of traffic between groups, but also the physical positioning of the nodes and their mobility pattern. The nodes that belong to the same group are expected to stay close to each other and the group is expected to share a common goal when moving.

The goal of this paper is to investigate how these community structures that occur in ad hoc networks because of their underlying social character influence the network performances. Of special interest is the question of how the link distribution density in the network, expressed via the social node degree distribution, affects the network performances in accordance with the community structures.

In order to pursue this topic we created several models of the logical and physical level of ad hoc nodes interactions creating socially based communication and mobility patterns that are socially based and reflect the small-world, scale-free and community forming phenomena of the network of users.

The rest of this paper is structured as follows: In section 2 the underlying social network models that incorporate the small-world phenomenon and the community structures, as well as the scale-free phenomenon and the community structures, are presented. Section 3 describes the way these network models are used for creating communication pattern and mobility scenarios for the ad hoc network performance investigation. In Section 4 the simulation scenarios are presented, while Section 5 gives an overview of the results obtained. Section 6 concludes the paper.

2 Modeling Social Networks of User Communities

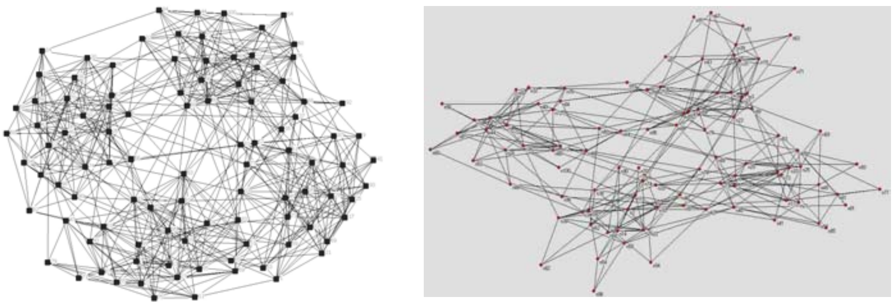
The complex network studies in the last decade have shown that social networks share some ubiquitous properties that have captured the interests of scientists from many different fields. These properties that have be found as an integral part of many natural and man-made networks are the small-world and scale-free phenomena.

The small world phenomenon [8] captures the so called low global separation in the network. Networks that exhibit the small-world phenomenon have a very small average path length when compared to the number of nodes in the network. For an example, 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 [9] that creates a network that has a large clustering coefficient (high local density), but also a small average path length. The large clustering coefficient is another feature that characterizes social networks implying the higher probability of two friends to have a mutual friend. However, one of the downfalls of the model is that the resulting network has a uniform distribution of the node degree, as well as the inability to create a network with a desired number of communities. In order to address the later problem we created a new small-world network model that allows for creation of a network with the same characteristics of the Watts-Strogatz model as well as the ability to form a given number of communities in the network. The small-world communities (SWcom) model is described in [3] and it 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. 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.

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 $p(x) = Ax^{-\alpha}$ 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. However, the main drawbacks of the Barabasi-Albert model are the low clustering coefficient and the lack of ability to capture the community structures in the network. Thus, we created the scale-free communities (SFcom) model presented in [4] that incorporates the small world phenomenon and the scale-free property in such a manner that the obtained network is actually 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. In this way, the obtained network also has a large clustering coefficient. The model tends to give representation of the real life situations wherein each group has at least one ‘group leader’ that is represented as a hub in the network.

The two proposed social network models were made in order to observe how the community structures influence the behavior of the ad hoc network on both the application and the physical layer of the network. The two variations of creating different communities offer another interesting insight in the network behavior. The SWcom offer a small-world network made out of nodes with a common node degree, thus creating a network that will be balanced when considering the frequency of interactions between nodes inside the community. The heavy load (in terms of interactions) can be found only at the nodes that act as groups interlinks.



a) SWCOM - 4 communities b) SFCOM – 4 communities

Fig. 1. Example social networks with 100 nodes created with the SWcom model (a) and the SFcom model (b) with 4 communities.

On the other hand, when considering the SFcom network, this egalitarianism is non existent. The distribution of links inside the groups is according to the power law distribution thus creating bottlenecks at each group leader (hub) in the network. At the same time, these hubs also have the duty to act as interconnection points for inter-group communication. For visual comparison, on Fig. 1 example networks obtained with both of the models are shown.

3 Community Based Communication and Mobility Patterns

Using the findings of the theory of complex networks, we created 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 main goal of the models is to realistically capture the social network of the ad hoc network users. These models are afterwards used to create traffic and movement generators that will mimic the way the ad hoc network is going to be used by its users in a real life situation. The models incorporate both the small world and the scale free properties while emphasizing the community structures which are constantly observed in the real social networks.

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 SWcom and SFcom model in combination with specialized custom made application layers for the widely used open source NS-2 network simulator [11].

Our custom application layers use the information read-in from the generated social network using the SWcom or SFcom 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 underlying social 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'). 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 layers, we created a traffic generator that generates traffic with a given offered load over the simulation time.

In order to be able to incorporate the community influence on the node physical positions and movement patterns, we also created another tool that serves as a mobility scenario generator which is a modified version of the community mobility generator [12]. The generator is modified so that it works as follows: first, it reads in the generated social network according to one of our models, secondly, using the Girvan-Newman modularity method [13] it finds the communities in the 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 within the boundaries of their respective community while sharing a common goal.

4 Simulation Scenarios

In order to investigate the impact of the different community structures on the ad hoc network performances we conducted several series of simulations. All of the simulations were performed on the SeeGrid infrastructure [14]. 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 [15], 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 social network with 4 communities which provided us with a network that has clustering coefficient and average path length that are closest to the ones observed in real life [2]. The additional parameters of both of the models are chosen so that 85% of the links in the network are links within the communities, while the rest 15% of the links are inter-community links.

One of the goals of the paper is to observe the influence of the existing community structures in the network on the logical and on the physical level separately for both of the social communities' models. Thus, the simulation scenarios also offer the possibility to use the created SWcom or SFcom social (information) network only on the logical (application) layer L, while the nodes are scattered and moving randomly in the complete simulation area P=GeomRND; or only on the physical layer P in which case the nodes are moving together within their communities, but the communication is completely random L=RND; or on both, physical and logical layers L and P wherein the communication and the movement pattern are according to the community modeling of one of the proposed models.

4 Impact of social communities on network performances

The first set of results is focused on presenting the ad hoc network performances when the network is modeled using the small-world and the scale-free communities social networks on the logical and/or physical layer of the network. The results obtained when the communities are modeled according to the SWcom are shown on Fig. 2, while the results obtained when the communities are modeled according to the SFcom are shown on Fig. 3.

The results presented on Fig. 2 allow for a fair comparison of the network performances obtained the traditional way with random traffic and movement together with the results obtained when modeling communities in the network using the small-world communities model. It can be concluded that taking into account the existing communities on the physical layer does not greatly change the behavior of the network, while the impact of the communities structures on the logical level is more than slight. The network performances rise rapidly when the traffic is modeled according to the social ties of the users. This is even more evident when both layers are modeled taking into account the small-world communities that are overlapping (L=SWcom and P=SWcom). An overall impression is that the performances are saturating when the offered load reaches 1 Mbps, while the maximum throughput achieved is also 1 Mbps. This shows that 1 Mbps is a maximum throughput that can be achieved in a network with a balanced, that is, uniform, traffic between the nodes of the community. This uniform traffic is a result of the clustered small world behavior where all of the nodes that belong to one community have identical node degree and the distribution of source-destination pairs of nodes is uniform.

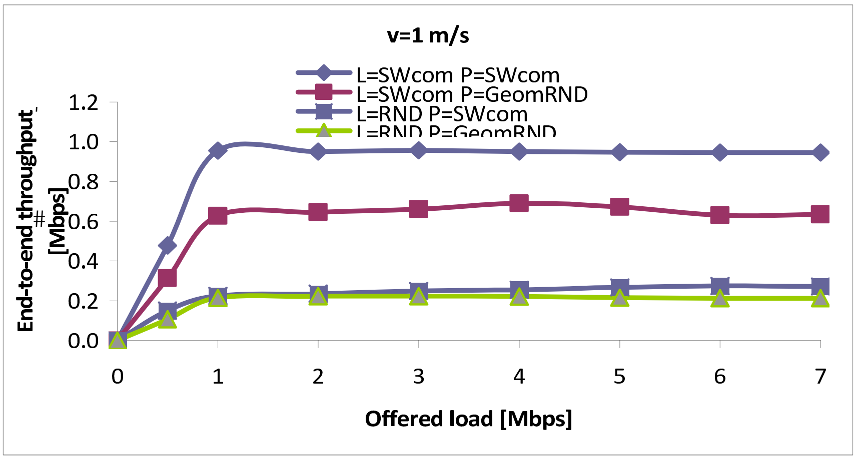


Fig. 2. End-to-end throughput in an ad hoc network modeled with and without small-world communities on logical and/or physical level using the custom SWcom application layer and movement generator for nodes that move with 1 m/s

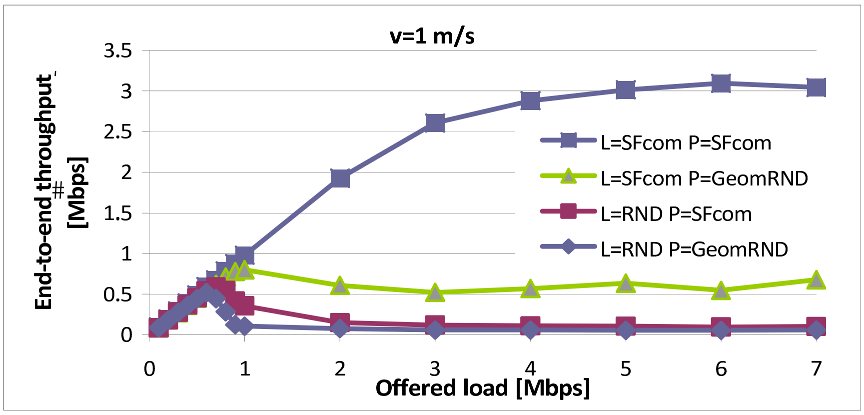


Fig. 3. End-to-end throughput in an ad hoc network modeled with and without scale-free communities on logical and/or physical level using the custom SFcom application layer and movement generator for nodes that move with 1 m/s

When the same analysis is done using the scale-free communities model there are some similar results, but also different trends in the obtained performances (see Fig. 3). The behavior of the network for communities only on the physical or on the logical level is very similar as it can be expected. However, when considering communities on both layers at once (please note that this case is the one to be found in real life situations), the network performances show different behavior. They reach more than 3 Mbps throughput for higher offered loads of 5 and 6 Mbps showing that the network does not get into saturation fast and allowing for a tremendous rising of the performances. This is somewhat peculiar while one is expecting to see lower performances because of the increased number of bottlenecks in this network model. However, care must be taken to consider that the network medium is shared and that in cases when in most of the communication the hubs are either source or destinations for the packet, it is much easier to solve the contention for the medium without the need for too many backoffs.

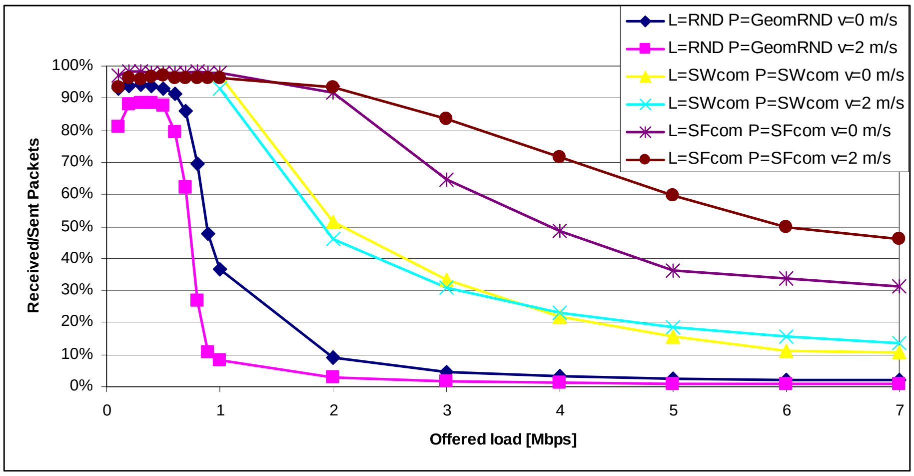


Fig. 4. Percentage of received over sent packets for network with and without communities modeled according to the SWcom or SFcom model for static and nodes that move with 2 m/s average speed

Fig. 4 offers some more insight on the ad hoc network performances from the perspective of how the percentage of received packets over the number of sent packets in the network changes when taking into account the social communities in the network using the small-world or the scale-free model instead of using the traditional random approach. It can easily be seen that while the random models predict only 1% of the packets to be delivered at their destinations for higher loads, when the traffic and mobility patterns depict the social activity of the network the simulations show that the percentage of received packets is several times higher than the expected and drops more slowly with the increasing load. Also, for the small-world model certain resilience to the node mobility is present, while in the scale-free communities case the node movement adds to the network performances increasing them for around 20% for higher loads. The increase of performances due to node mobility is one of the intrinsic characteristics of ad hoc networks and these sets of simulations just confirm this fact [5].

A comparison of the achieved network performances for various node speeds is presented on Fig. 5. The relative difference in the end-to-end throughput for the different models is clearly visible for static and nodes moving with 1, 2 or 5 m/s. The small-world communities modeled on both the logical and physical level show up to 10 times better performances than the traditional random scenarios. At the same time, the scale-free communities show improvements over the traditional models that are over 20 times higher. When comparing the two different communities types, one can conclude that the scale-free communities show outstanding performances which are in average 2 times better than the small-world communities. This is due to the distribution of the traffic inside the communities since in the both cases the number of community members as well as the number of communities is the same, which means that on the physical level, the modeling is done in the same manner since the mobility generator is concerned with these two parameters only.

The results clearly show that as much as the very existence of communities plays a major role in determining the network performances, the very distribution of the traffic in and outside these communities is a variable that has a vast impact on the network throughput.

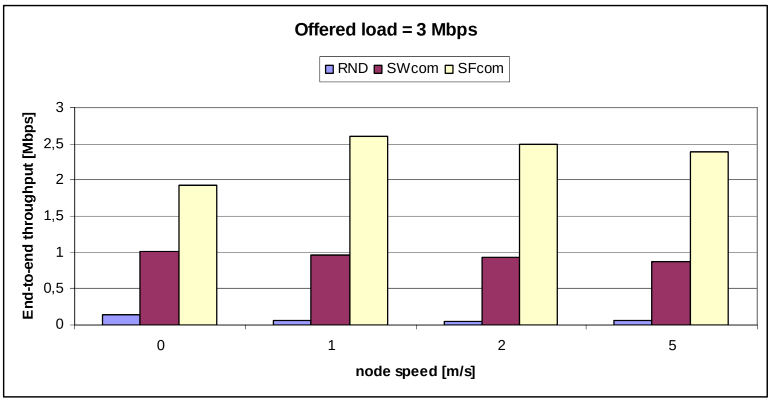


Fig. 5. Comparative analysis of the ad hoc network performances when the application and physical layers are modeled traditionally or with communities models for various node speed

5 Conclusion

In this paper we investigated the impact of the social communities structures that exist between the users of ad hoc networks on the actual network performances expected in real life situations. We argue that since the ad hoc network is going to be used as a tool to share information between a given group of people, the usage of the network in terms of traffic pattern and node mobility pattern is going to be governed by the rules of the social network established between the network users. Thus, care must be taken that while studying the network we work with scenario generators that will mimic this social behavior.

From this point of view, our main goal was to establish how the social grouping of users influences the overall throughput of the network. For this purpose we model the network users using small-world and scale-free communities on both the logical and the physical level. The results show that the communities on physical level cause a small rise in the network performances, while the communication pattern defined over communities on the logical level has a greater impact on the network performances.

Further more, when these two types of communities coincide, the ad hoc network performances are 10 to 20 times better when compared to the traditional simulation scenarios that are based on the random traffic and mobility patterns.

One of the main findings in this paper is that while the communities themselves have a great impact on the network performances, the way the traffic is distributed within the communities has an equal or even greater impact on the network behavior. Moreover, the results show that the power law distribution inside the community as well as in the social network as a whole creates focal points in the network traffic (the group leaders, or hubs in the network) which actually help to increase the network throughput by lowering the contention for the shared medium in the network.

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