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Small world phenomena and performances of wireless ad hoc networks

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Abstract—The groups of people that use an ad hoc network form a social network that exhibits small world properties. In this paper the impact of small world phenomena in application layer network on performance of ad hoc network is investigated. We show that small world properties have a big influence on the performance taking into consideration different routing protocols and network area shapes. In order to quantify the influence of small world properties on ad hoc network performances, two parameters are used: clustering coefficient and average hop distance. The average hop distance is a measurement for overlapping of logical and physical network. We also propose a new algorithm for generation of small world networks.

Key words: — ad hoc network, small world, performance, application layer

1 Introduction

An ad hoc network is a collection of wireless mobile nodes dynamically forming a temporary network without the use of any existing network infrastructure or centralized administration. Nodes in an ad hoc network can act as both hosts and routers since they can generate and forward packets. Since there is no existing communication infrastructure (e.g., a wired or a fixed wireless base station), nodes in an ad hoc network are expected to act cooperatively to establish the network "on-the-fly" and route data packets over possibly multiple hops. Node mobility and limited power introduce rapid changes in network topology, connectivity and links characteristics.

Most of the recent studies have addressed mainly the technical side of performances of ad hoc networks taking into consideration only random communication between the nodes corresponding to the random graphs theory. However, the interesting features of real-world networks concern the fact that they are not like random graphs in several revealing ways [7], which features, on the other hand, suggest using non-random communications scenarios between ad hoc network users. Johansson et al. [8] made a comparison of three wireless mobile ad-hoc. In [9], non-random communication is employed in order to observe the impact of clustering in different layers on wireless ad hoc network performances.

The main application of wireless mobile ad hoc networks is to offer services for situations wherein groups of people come together for a short time and share information [2]. The groups of people that use the ad hoc network form a certain type of real social network. Watts and Strogatz [4] have shown that the connection topology of biological, technological and social networks is neither completely regular nor completely random but stays somehow in between these two extreme cases. This particular class of networks, named small worlds in analogy with the concept of the small-world phenomenon observed more than 30 years ago in social systems [5], are in fact highly clustered like regular lattices, yet having small characteristic path lengths like random graphs. Thus, real social networks exhibit clustering ; that is the tendency of two individuals who share a mutual friend to be friends themselves [3]. Existence of clustering in network of people who use ad hoc network to communicate and share information, implicates clustering in the application layer of an ad hoc network. In order to quantify the influence of the small world phenomena to ad hoc network performances, we use two parameters: average hop distance and clustering coefficient.

2 SMALL WORLD IN AD HOC NETWORK

Users that use an ad hoc network form a social network that has small world properties. This social network is expressed on the application layer and is called logical network or application layer network. The underlining ad hoc network is called physical network and is different from the application layer network (Fig. 1).

2.1 Average Hop Distance

One of the structural properties of small world networks is their characteristic path length. The characteristic path length is defined as the number of edges in the shortest path between two vertices, averaged over all pairs of vertices. This parameter has not great influence on performance of ad hoc network. The path length between two nodes in logical network is obviously different from corresponding path length in physical network, and can be greater or lower depending on the physical proximity of the nodes and positions of the routing nodes. The correspondences of the links between logical and physical network result in increased overlapping, and thus in better performances of the whole system

For evaluation of the dependence of performances from the overlapping of logical and physical network, we introduce the average hop distance parameter. The shortest hop distance h_{ij} between nodes i and j is the minimum number of hops needed to send a packet from node i to another node j. By definition $h_{ij} \geq 1$, and $h_{ij} = 1$ if there is a direct connection between node i and j (node j is in transmission range of node i) in the underlining ad hoc network. The average hop distance H of the logical $G_L(V_L,E_L)$ and physical network $G_P(V_P,E_P)$ is defined as the average of the shortest hop distances between the nodes that are connoted in G_L,

$$H(G_L, G_P) = \frac{1}{|E_L|} \sum_{i \neq j \in V_L} h_{ij} \qquad (3.1)$$

$|E_L|$ gives the total number of links in the logical network G_L. Of course, the assumption that G_P is connected is crucial in the calculation of H. It implies that there is at least one path connecting any couple of vertices with a finite number of steps.

3.2 Clustering Coefficient

Clustering coefficient measures the cliquishness of a typical neighborhood and it is a local property.

The basic concept of the clustering idea is to group some "neighboring" nodes together into a cluster. As pointed out by Watts [3] real-world networks show strong clustering or network transitivity. A network is said to show clustering if the, probability of two vertices being connected by an edge is higher when the vertices in question have a common neighbor. That is, there is another vertex in the network to which they both are attached. The clustering effect is measured by a clustering coefficient C, which is the average probability that two neighbors of a given node are also neighbors of one another.

Let us focus first on a selected node i in the network, having k_i edges which connect it to k_i other nodes. If the first neighbors of the original node were a part of a clique, there would be $k_i(k_i - 1)/2$ edges between them. The ratio between the number E_i of edges that actually exist between these k_i nodes and the total number $k_i(k_i - 1)/2$, gives the value of the clustering coefficient of node i [10]. The clustering coefficient of the whole network is then the average of all individual clustering coefficients.

$$C_i = \frac{E_i}{k_i(k_i - 1)/2} \text{ and } C = \frac{1}{N}\sum_{i=1}^{N} C_i \qquad (3.2)$$

In many real-world networks the clustering coefficient is found to have a high value, from a few percent to 50 percent or even more [11].

According to the previously defined logical and physical networks, we also define two types of clustering in an ad hoc network: logical (application) and physical (topological). While logical clusters

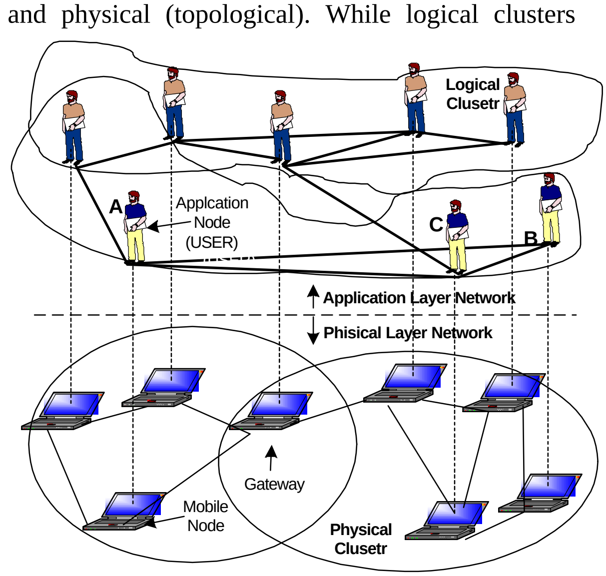

Figure 1. Application Layer and Physical Layer clustering

represent people friends in an application view, physical clusters are based on the topological connectivity of the mobile devices (see Fig. 1). To enable communications between nodes, called gateways, belonging to different clusters there must be nodes that belong to more than two clusters at the same time.

4 SMALL WORLD NETWORK GENERATION

Some of the main applications for the ad hoc networks are: military solders in the battlefield, a conference or campus setting; the forestry or lumber industry, temporary offices, and rescue mission operation. In all this applications the users of the ad hoc network are divided into groups. The users belonging to a same group are strongly connected (there exists clustering) and often share the same physical proximity. The main communication is between users in a same group, but there are communications between users belonging to different groups.

The small world network topology used in [4] is a one-parameter model that interpolates between an ordered finite dimensional lattice and a random graph. The algorithm starts with a ring lattice with N nodes in which every node is connected to its first K neighbors (*K*=2 on either side). After that, each edge of the lattice is randomly rewired with probability *p* such that self-connections and duplicate edges are excluded. Another variant of the previous model was proposed in [12]. With this proposed models clustering can be easily modeled, but modeling of grouping and physical proximity of nodes is more complicated.

4.1 Small World Network Generation Algorithm

We define algorithm for generation of small world networks that satisfies the previously specified properties. Input parameters for the proposed model are: number of groups (clusters) *U*, number of nodes per cluster *M*, average degree of node *d*, and percentage of in-cluster communications *a*. The algorithm result is an *N*x*N* connection matrix, where *N*=*M***U* is the total number of nodes (users). The first *M* nodes belong to the first cluster; the nodes with numbers *M*+1 to 2*M* belong to the second cluster, etc. First, in each cluster *M***d***a* links between randomly chosen nodes are created. After that *N***d**(1-*a*) links between nodes belonging to different clusters are created. Using the algorithm it is possible to model a wide range social groups i.e. from highly interconnected to strictly independent.

A node from generated network is connected with nodes in same cluster with probability p_i and with nodes in different clusters with probability p_o,

$$p_i = \frac{d\,a\,M}{M(M-1)/2} \;\; ; \;\; p_o = \frac{d(1-a)N}{(N-M)N/2} \qquad (4.1)$$

Let the random variable *X* be binomial distributed with parameters (*p*, *N*), where *N* is number of independent trials and *p* is the probability for success in an individual trial. The probability that *X*=*k* is given by

$$P\{X=k\} = \binom{N-1}{k} p^k (1-p)^{N-1-k} \qquad (4.2)$$

The average value of the random variable *X* is $E\{X\} = Np$. The neighbors of a given node *v* can be divided in two groups, neighbors in the same cluster (group *S*) and neighbors in different clusters (group *T*). The number of neighbors in the same cluster X_i is binomially distributed random variable with parameters (p_i, *M*-1), its average value is $E_{Xi} = E\{X_i\} = (M-1)\,p_i$. The number of neighbors in different clusters X_o is binomially distributed random variable with parameters (p_o, *N*-*M*), its average value is $E_{Xo} = E\{X_o\} = p_o(N-M)$.

Now lets select one node *s* of the *S* group of neighbor nodes in the same cluster. The selected node *s* can have neighbors in same cluster and in different clusters. The number of neighbors nodes in the same cluster that also belong to group *S* is a random variable X_{ii} that is binomially distributed with parameters ($p_i(E_{Xi}-1)/(M-2)$, *M*-2); its average value is

$$E_{Xii} = \left(p_i \frac{E_{Xi}-1}{M-2} \right)(M-2) = p_i(E_{Xi}-1) \qquad (4.3)$$

By similar arguments, we find that the average number of neighbor nodes in different cluster is

$$E_{Xio} = \left((p_o E_{Xo})/(M-N)\right)\cdot(N-M) = p_o E_{Xo} \qquad (4.4)$$

Lets select one node *t* from the other group of neighbor nodes *T*. The selected node *t* also can have neighbors in the group *S* and *T*. The average number of neighbors nodes in group *S* is X_{oi} and is given by

$$E_{Xoi} = \left((p_o E_{Xi})/(M-1)\right)\cdot(M-1) = p_o E_{Xi} \qquad (4.5)$$

The nodes that are in group *T* can belong to the same cluster or to a different cluster. Let *J* be the number of nodes in group *T* that are divided into *U*-1 clusters. We define a random variable *Y* as the number of nodes in one selected cluster. *Y* is binomially distributed with parameters (1/(*U*-1), *J*). The number of links between nodes in the selected

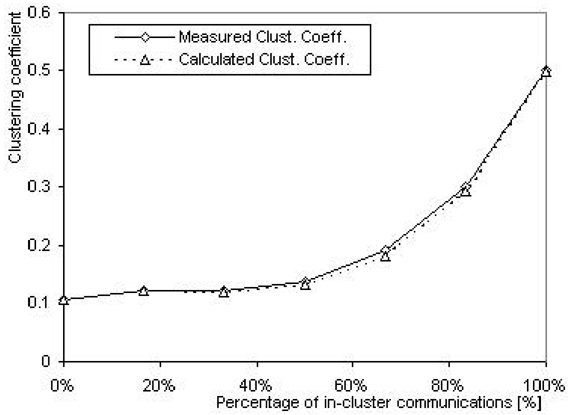

Figure 2. Measured and calculated clustering coefficeint depending on the in-cluster communication percentage

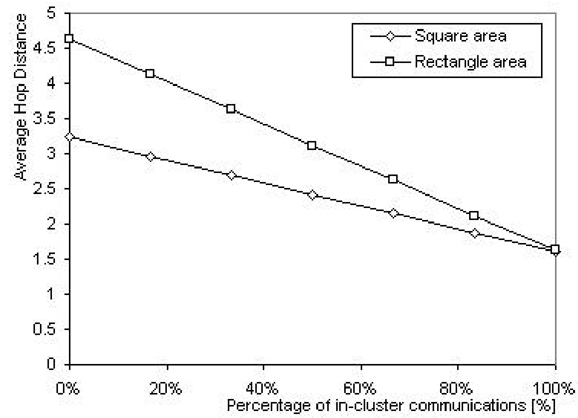

Figure 3. Average hop distance for square and rectancle area depending on the in-cluster communication percentage

cluster is $Z=Y(Y-1)/2$. The average value of Z is given by

$$E\{Z\}=\sum_{k=0}^{J}\frac{k(k-1)}{2}\binom{N-1}{k}\left(\frac{1}{U-1}\right)^{k}\left(1-\frac{1}{U-1}\right)^{J-k} \quad (4.6)$$

Solving (4.6) we get $E\{Z\}=(J(J-1))/(2(U-1)^2)$. The total number of links in all U-1 clusters Z_T is

$$Z_T=(U-1)\frac{J(J-1)}{2(U-1)^2}=\frac{J(J-1)}{2(U-1)} \quad (4.7)$$

All of the possible links between J nodes is $J(J-1)/2$, and the fraction of links connecting nodes in same cluster z_f is

$$z_f=\frac{Z_T}{J(J-1)/2}=\frac{1}{U-1} \quad (4.8)$$

Now lets select the node from group T. The average number of neighbors nodes in group T is X_{oo} and is given by

$$E_{Xoo}=(E_{Xi}-1)\frac{z_f p_i+(1-z_f)p_o}{K-M-1}(K-M-1) \quad (4.9)$$

The total number of links between neighbors of node v is

$$E_v=\frac{E_{Xi}(E_{Xii}+E_{Xio})+E_{Xo}(E_{Xoi}+E_{Xoo})}{2} \quad (4.10)$$

The clustering coefficient C of the generated ad hoc network is

$$C=\frac{E_v}{(E_{Xi}+E_{Xo})(E_{Xi}+E_{Xo}-1)/2} \quad (4.11)$$

4.2 Physical Network Model

Modeling of physical proximity of nodes is achieved by dividing the area in U sub areas. In each sub area M nodes belonging to a same logical cluster are randomly scattered. This enables creation of clusters on physical layer, and makes the overlapping of logical and physical clusters easy.

4.3 Ad Hoc Network Example

For the performance analysis of small world phenomena, we considered a wireless ad-hoc network placed on area of $1km^2$. In order to be sure, with a probability of at least p, that no node in an ad hoc network with N>>1 nodes and homogeneous node density $r=N/A$ nodes per unit area is isolated, the node transmission radius r according [13] must be set to

$$r\geq\sqrt{\frac{-\ln(1-p^{1/N})}{p}\cdot\frac{A}{N}} \quad (4.12)$$

The no-isolated-node probability is a measure of the ad hoc network connectivity and here it is used to calculate the number of nodes needed to achieve connected ad hoc network for a given area A and transmission range r. Solving (4.12) for $A=10^6m^2$, r=250m and p=0.9999 we get N=69 nodes. Taking into account the borders effects we chose N=100 nodes, thus providing connected ad hoc network.

The logical network is generated with the proposed generation algorithm. The values of parameters are: number of clusters U=4, number of nodes per cluster M=25, average degree of node d=12, and percentage of in-cluster communications varied from 0% to 100%. The dependence of the clustering coefficient on the in-cluster communications is shown on Fig. 2. The overlapping of the measured clustering coefficient and the calculated clustering coefficient using (14) can be seen. In the simulations scenarios two area shapes where nodes are placed are used: square and rectangle. The square area is with dimensions 1km x 1km and the rectangle area is 0.5km x 2km. Both have 0.5km x 0.5km sub areas. When physical clustering exists in each of the sub areas 25 nodes are randomly placed, and when there is no physical clustering all 100 nodes are randomly scattered in the whole area. The dependence of average hop distance on the in-cluster communications for square and rectangle area is presented on Fig. 3. It can be seen that there is a linear relationship between the average hop distance and the in-cluster communications. When all communications are in a same cluster both of the areas have identical average hop distance as expected. For smaller in-cluster communications the rectangle area has greater average hop distance as a result of the greater distance between nodes.

5 Simulation Methodology

For the purposes of simulating and analyzing the behavior of small world phenomena in ad hoc networks, NS-2 [6] network simulator from Lawrence Berkley National Laboratory was used as one of the most accurate and popular ones [14].

5.1 Application Protocol with Clustering

NS-2 does not include an application layer protocol that is aware of any logical cluster division of a population of nodes. Hence, we created custom type of application layer protocol that has this feature and supports the previously proposed algorithm for generation of small world networks. By the means of its application layer, each node knows which its friends are (nodes in same cluster), or, more exactly, which are the nodes it can communicate with. When a node communicates only with its friends, we have logical clustering. Since TCP is adding a lot of complexity and thus masking clustering effects, the created application protocol uses UDP communication only.

5.2 Routing Protocols

The most vital part of an ad hoc network is the routing protocol. NS-2 supports four ad hoc routing protocols: DSDV, DSR, AODV and TORA. In the simulations two different routing protocols are used to compare impact of clustering on their performance. We chose DSR [16] and AODV [15] because they have better performance then DSDV and TORA [6][7].

5.3 Scenario Characteristics

For the performance analysis of small world phenomena, the example wireless ad-hoc network defined in 4.3 is used. All nodes communicate with identical wireless radios. At the physical layer, a radio propagation model supporting propagation delay, omni-directional antennas, and a shared media network interface is used. The IEEE 802.11 Medium Access Protocol is employed at the Link Layer level, and transmission range up to 250m.

5.4 Performance Metrics

In this paper the following performances metrics are used: end-to-end throughput, total throughput and clustering performance factor. End-to-end throughput is the total amount of bits received by all nodes per second and is measured in bits per second (bps). Total throughput is the total amount of bits transferred through the ad hoc network, and it is calculated by multiplying end-to-end throughput by the average hop distance. In order to quantify the impact of clustering to performance of the ad hoc network we introduce a new metrics called clustering performance factor (*CPF*). *CPF* is defined as a ratio of achieved end-to-end throughput with clustering and end-to-end throughput without it [11].

6 Simulation Results

We have created and tested several simulation scenarios. Messages from the application protocol are sent periodically during simulation time. Each period a particular percent of sending nodes is chosen. In the case when the logical network has small world properties (logical clustering) each of the sending nodes randomly selects one friend node and sends a message to it. If there isn't logical clustering each of the sending nodes randomly selects any node and sends message to it. Each simulation scenario is defined by specifying the following parameters: logical and physical clustering, offered load, packet size, percent of nodes that send messages and routing protocol.

6.1 Routing Protocols: AODV vs DSR

In the first set of scenarios the impact of small world phenomena on performance of ad hoc network when AODV and DSR routing protocols are used is investigated. The offered load is varied from 0.1Mbps to 7Mbps (1Kbps to 70Kbps per node). The area shape is square. Three scenarios are simulated:

1. Logical clustering with physical clustering (L-1 P-1), i.e. all nodes from logical cluster are placed in the same physical cluster;
2. Logical clustering with no physical clustering (L-1 P-0), i.e. nodes from one logical cluster are randomly placed on whole area.
3. No logical clustering but physical clustering only (L-0 P-1), i.e. there are no logical clusters and the nodes are placed like in the first scenario

Since different placement of nodes leads to different performance in an ad hoc network, in the

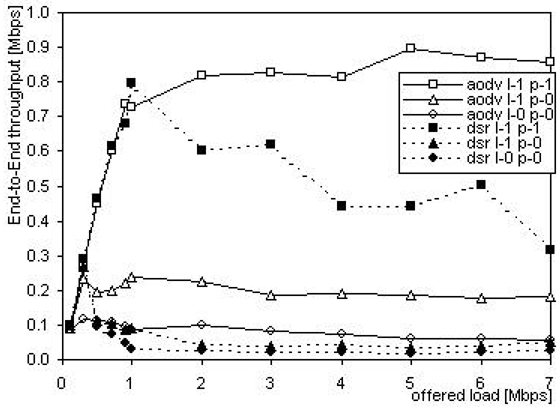

Figure 4. Impact of small world phenomena to end-to-end troughput for AODV nad DSR depending on the offered load

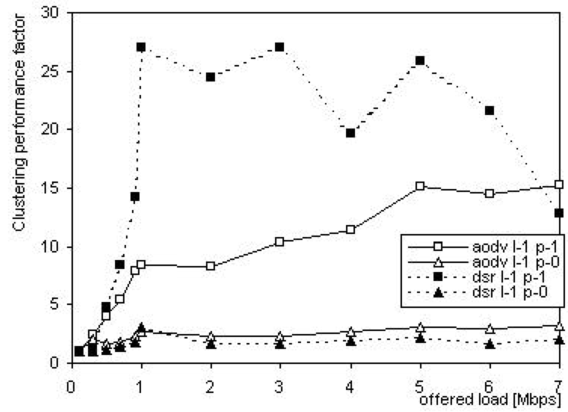

Figure 5. Impact of small world phenomena to CPF for ADOV and DSR depending on the offered load

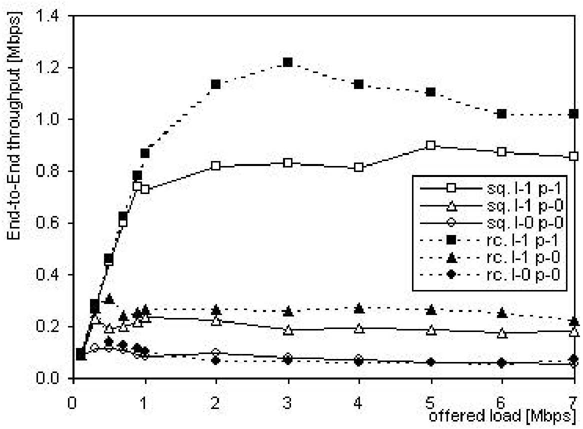

Figure 6. Impact of small world phenomena to end-to-end troughput for square(sq) and rectangular (rc) area depending on the offered load

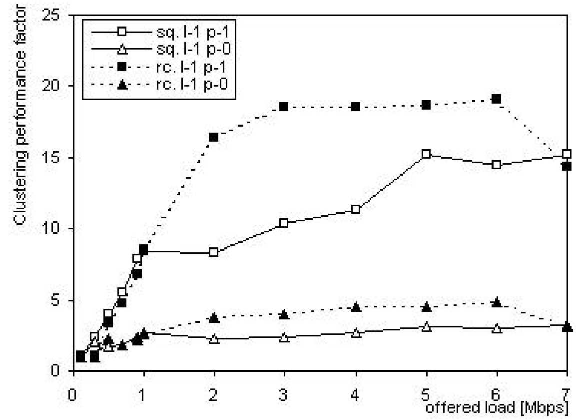

Figure 7. Impact of small world phenomena to CPF for square(sq.) and rectangular (rc.) area depending on the offered load

third scenario we use the same node placement as in the first scenario in order to compare impact of small world phenomena on the same ad hoc network topology. We did not present results for scenario without any clustering (L-0 P-0) because simulation results are almost equal to the results form the third scenario as one could expect. In case of logical clustering 83% of communications are within the nodes of the same cluster and 17% are within the nodes of different clusters.

Fig. 4 presents the impact of small world phenomena to end-to-end throughput when AODV and DSR routing protocols are used. The first scenario (L-1 P-1) where logical and physical clustering exists shows much better performance than the third scenario (L-0 P-1). The second scenario (L-1 P-0) shows better performance than the third scenario because nodes communicate only with their friends, and after routes to all friends are discovered, there is no additional routing layer overload. The third scenario has the lowest end-to-end throughput because of the random pattern of communications. The AODV routing protocol shows better performance than DSR especially when offered load increases as a result of the worse performance of DSR at high loads.

The CPF when AODV and DSR routing protocols are used is shown on Fig. 5. This metric shows interesting results. The first scenario (L-1 P-1) shows much better performance than the third scenario (L-0 P-1), CPF grows up when offered load increases as a consequence of more faster congestion of unclustered ad hoc network. The second scenario (L-1 P-0) also shows better performance than the third scenario. When the offered load is lower, and clustering exists at logical and physical layer, the performance of the ad hoc network using DSR increases much more (27 times) then using AODV (8.3 times). However, at higher loads, AODV performs better. The end-to-end throughput in AODVs case is higher than in DSRs case for all offered loads greater than 1Mbps.

6.2 Area Shape: Square vs Rectangle

In the second set of scenarios, comparison between performances of ad hoc network placed on different area shapes is made. The used routing protocol is AODV. The scenarios settings are the same as previous, when routing protocols were compared. The impact of small world phenomena to

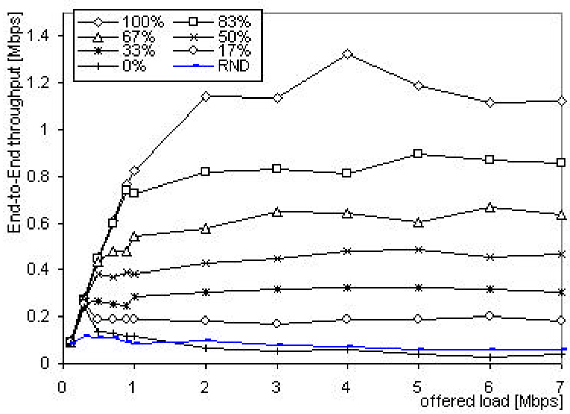

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Figure 8. End-to-end throughputs for various in-cluster communications percentage depending on the offered load

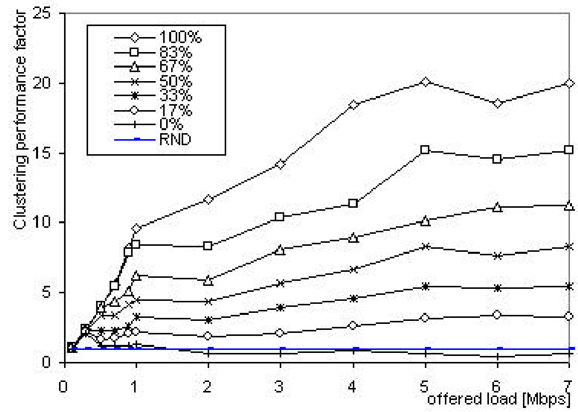

Figure 9. Clustering performance factor for various in-cluster communications percentage depending on the offered load

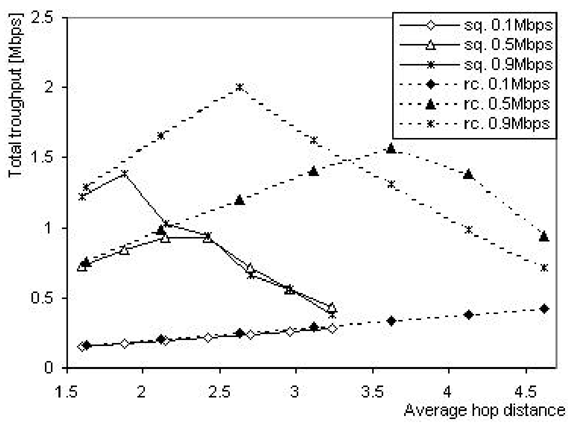

Figure 10. Total throughputs for various small offered load depending on the charachteristic hop distance
(sq. – square area, rc.- rectangle area)

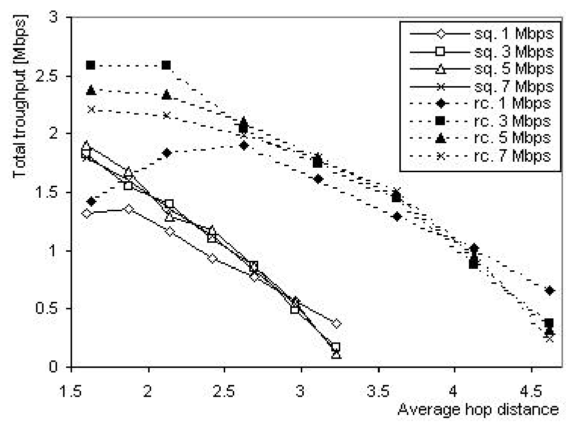

Figure 11. End-to-end throughputs for various large offered load depending on the charachteristic hop distance
(sq. – square area, rc.- rectangle area)

end-to-end throughput in the case when area shape is square or rectangle is presented on Fig. 7. The ad hoc network placed on rectangular area shows much better end-to-end throughput for the first (L-1 P-1) and second scenario (L-1 P-0), but has worse performances when there is no clustering (L-0 P-1). The better performance of the rectangular area ad hoc network is a result of the greater possibility for parallel communications when logical network has small world properties. When communications between nodes are random then the better performances of the square area ad hoc network is a consequence of the smaller average hop distance between nodes that communicate. The CPF for rectangular area ad hoc network is also greater than CFP for square area. The CFP for different area shapes is shown on Fig. 8.

6.3 Clustering Coefficient

In this set of seven scenarios, at logical layer we use small world network with different clustering coefficient. For achieving clustering coefficient from 0.1 to 0.5 (like in real social networks) the in-cluster communications are varied from 0% to 100%. For all scenarios nodes are also clustered at physical layer. For comparison of results random traffic (without logical clustering) scenario is made. All scenarios are tested using the AODV routing protocol . The area shape is square.

Fig. 8 presents the impact of in-cluster communications percentage on end-to-end throughput. The first scenario (100%) where all communications are between the nodes in the same logical and physical cluster, shows highest end-to-end throughput according to the decreased interference between wireless transmissions and possibility of parallel communications in different clusters when the nodes that communicate are on distance greater than the transmission range. In the other scenarios, the end-to-end throughput decreases together with the percentage of communications between nodes in the same cluster. The last scenario (0%) where all communications are between nodes in different clusters has the lowest end-to-end throughput, lesser than the end-to-end throughput of the referent random traffic scenario. This small end-to-end throughput is a consequence of the fact that all communications are within nodes that are on average greater distance than that in the random traffic scenario. The CPF for different percentages of in-cluster communications, is shown on Fig 9. The first scenario (100%) shows to 20 times (for 6Mbps) better performance than the random traffic scenario. Other scenarios have lower CPFs. It can be seen that CPF grows up when the percentage of in-cluster communications increases.

6.4 Average Hop Distance

The average hop distance depends linearly on in-cluster communications but has different values for different area shapes. We made different charts for it. The average hop distance is from 1.6 to 3.3 for square area, and from 1.6 to 4.7 for rectangle area.

Fig. 10 presents the total throughput depending on the average hop distance for various small loads. It has two phases: increasing phase to some critical average hop distance when it starts to decrease and enters a congestion phase. The critical average hop distance is the point where the capacity of network is reached. After this point the ad hoc network enters the congestion phase and the increasing of average hop distance leads to decreasing total throughput. The critical average hop distance point is smaller for higher offered load because of the faster reaching of the capacity of the ad hoc network.

It can be seen that the total throughput has maximum that is reached at the critical average hop distance point. This maximum is the capacity of ad hoc network for specified offered load and average hop distance. The capacity of an ad hoc network is lesser for smaller offered loads, as a consequence of the bigger average hop distance. The bigger average hop distance results in more hops and thus more routing overhead in the ad hoc network, which leads to reduced useful capacity. The capacity of square area ad hoc network is smaller than the capacity of rectangle area ad hoc network, because of smaller possibilities of simultaneous transmission. For large loads, (see Fig. 11) the capacity of ad hoc network is reached with smaller average hop distances and the total throughput is decreasing constantly with the increasing average hop distance. Exception is only 1Mbps offered load in rectangle ad hoc network that reaches capacity at average hop distance 2.7.

7 CONCLUSION

In this paper, the influence of small world phenomena to the performance of ad hoc networks was investigated. Analyzing real social networks and real applications of ad hoc networks it can be concluded that application layers show small world properties.

In order to quantify the influence of small world properties to performance of ad hoc network two parameters are used: clustering coefficient and newly introduced average hop distance as a measure for overlapping of logical and physical network. In order to test the impact of small world properties to performance of an ad hoc network, a new algorithm for generation of small world networks was proposed. The influence of routing protocols to performance was studied trough comparison of ADOV and DSR, while the impact of the area shape was investigated trough evaluation of performances for square and rectangular ad hoc network area. The total throughput has maximum that is reached at critical average hop distance point, that represents the capacity of the ad hoc network for specified offered load and average hop distance.

The main goal when using a network is to put it to work at a maximum performances point. This paper shows the existence of that point for ad hoc wireless networks and the way to reach this point.

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