Position Guided Local Routing and Reconfiguration in Mobile Telecommunication Networks with Scale-Free Topology*

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***Abstract*— Assuming wireless communication in scale-free networks, the local routing model can be extended with a novel approach which takes spatial information into account as well. The properties of the proposed model are analyzed in this paper also when the nodes of the network are moving along straight lines in the unit square. Furthermore, we analyze how reconfiguration affects the throughput and energy efficiency of the network.**

***Index Terms*— Wireless networks, Local routing, Scale free networks, Reconfiguration**

I. Introduction

Routing, the most important networking layer function in packed-switched telecommunication networks [1] is widely studied both in fixed [1], [2] and mobile ad hoc networks [3], [4], [5]. Regarding the topology of medium and large scale communication systems, the tool of scale-free networks is often (but not always [6]) an acceptable approach to describe the communication topology [7]. Traffic and transport in complex networks has been studied in [8], [9]. In such very large networks, it may be not possible to acquire complete information about the network topology, thus simple approaches as shortest path routing can not be applied. This implies the application of non-complete information and local rule-based routing mechanisms. Local routing on scale-free networks has been studied in several papers [8], [10], [11], [12], [13], [14], [15].

The network performance is usually measured in the vast majority of these articles by the value (denoted usually by η) which describes the jamming level of the network, and the average packet traveling time. This latter is in strong correlation with the average number of hops a package performs on the network (in addition it also depends on the time which the package spends in queues). However, in wireless telecommunication applications, not only the connection topology but also the positions of the agents play significant role, since the transmission cost grows with the square of the distance. One distinguished topology is the scale-free network in which the degree distribution is exponential. Such networks have been identified in natural self-organizing structures [16]. Scale-free network formation in the corresponding Euclidean space has been studied in [17].

Our aim in this article is to apply the scale-free network traffic analysis in wireless communication context, thus considering spatial information and transmission energy cost as well. The scale free property may be a relevant assumption regarding the topology of the network, since in this network the average distance between two random nodes is lower than in a random graph due to the high degree hubs, and such structures are easily generated with the preferential attachment algorithm [18]. As a first step of this approach we study the local routing based communication among nodes moving in a closed space, and analyze how the utilization of spatial information and reconfiguration due to movement affect the throughput, speed and energy optimality of the network.

II. Materials and Methods

For the generation of the initial network we use the geometry-modulated version of the Barabási-Albert algorithm [18], as described in [17]. A seed with n_{seed} nodes and m_{seed} link is used, and an iterative process is applied during which in each time step a new node with random position in the unit square is introduced and is randomly connected to m previous nodes. Any of these m links of the new node introduced at time t connects a previous node i with an attachment probability $\pi(t)$ which is linearly proportional to the degree $k_i(t)$ of the i-th node at time t and to l^β, where l denotes the Euclidean distance of the new node and node i, and β is a free parameter. $\beta < 0$ corresponds to the case when nodes are more likely to connest closer ones. We call the resulting graph the *communication graph*.

$$\pi_i(t) \sim k_i(t) l^\beta \tag{1}$$

We assume that the node moves with constant velocity along straight lines. The direction and speed are chosen with uniform distribution from $(0, 2\pi)$ and $(0, v_{max})$ respectively, and recoil on the edges.

The traffic model is described as follows [10]: at each time step, there are R packets generated in the system with randomly chosen sources and destinations. The buffer (queue) size of the nodes is assumed to be infinite, but any node can forward at most C (finite) packets in each time step. To make the model independent of the update order of the nodes, we assume that one packet can hop only once during a certain time step. To navigate packets, each node performs a local search. If the packet's destination is found

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among the neighbors, it is delivered directly to its target. Otherwise, it is forwarded to a chosen neighbor via the local routing mechanism. The assumed local routing mechanism is based on the algorithm described in [10] (packets are more likely to be delivered to high degree neighbors) with a slight modification which allows the model to take into account the node positions during the routing. We assume that each packet in the network holds information about its destination node and that the nodes are aware of each others actual positions even if they are not connected in the communication graph, and will use this information while carrying out the packet forwarding. In other words we assign a destination position to each packet which is always equal to the position of the destination node of the actual packet.

In practice this will mean that while the protocol described in [10] assumes that in the case when the destination node is not present in the actual node's local neighborhood, nodes forward their packets to one of their neighbors taking into account only the degree of the actual neighbor, the protocol defined in this article will assume that node i forwards packet p to node j more likely if the position of node j is closer to the destination position of packet p. However, as the most simple approach, the proposed algorithm takes the spatial information into account only in a binary manner. Formally the packet p is forwarded from node i to its neighbor j according to the preferential probability

$$\Pi_j = \frac{k_j^\alpha}{\sum_m k_m^\alpha}\delta, \quad (2)$$

where the sum runs over the neighbors, and $\delta = \delta_1$ if neighbor j is closer to the destination position of packet p and $\delta = 1 - \delta_1$ if it is not. Here we have to note that we assume that the nodes are aware of each others position. The question how realistic this assumption is may be subject to future studies, but in the case when the agents use a independent systems for navigation and communication, the scenario may be of interest. Furthermore, an additional consideration for not using the exact distance in the decision equation may be that if favored nodes are more close to the destination position, and if the i-j distance is large, this would lead to the preference of long-distance transmissions, which are not energy-optimal.

Similar to [10], we assume that in a certain network none of the tokens may take the same edge again. There is a theoretical possibility that this assumption may lead to deadlock situations, but in practice the number of these scenarios is so low that they do not influence the results.

A. Reconfiguration

One main aim of this paper is to analyze how reconfiguration affects network performance. Under reconfiguration we mean the re-generation of the communication graph while the position of the nodes are unaffected. The intuition is that as the nodes are moving with time the performance of the network from energy optimality point of view is affected. Consider e.g. the following scenario: It is easy to see that in the initial generation of a communication graph, nodes in the middle are more likely to have a higher degree, since they have neighbors from all sides, who are likely to connect with them. Later these high degree nodes may move towards the edges, which implies that their average distance from a given random node grows. This will result in higher transmission cost.

The reconfiguration takes place as follows. In the first step, n_{seed}^r points are chosen at random. To each of these points we assign m links, based only on the distance of the nodes ($\pi_i(t) \sim l^\beta$). After this seed is ready the remaining points are connected to the structure with the same algorithm which is used in the initial generation of the *communication graph*. We characterize the energy need of the reconfiguration process with the constant E_{RC}.

As the method of reconfiguration is given, a reconfiguration strategy determines the time values at which a reconfiguration is carried out. Furthermore, as mentioned earlier, we note that each packet contains a list of the edges it's been traveled (and avoids these edges in the following) - this list is cleared at each reconfiguration.

III. Results

We will analyze network performance with the following measures:

- Total transmission energy (E_{TR}) - we assume that the energy cost of a single transmission is equal to the square of the distance over which it is carried out. If we sum this value over all transmissions of a time step and over all the time steps of the simulations we get E_{TR}.
- Total energy consumption E_T - the sum of E_{TR} and the energy needed for the reconfiguration procedure.
- The average packet traveling time or arrival time $\bar{\tau}$ - it is straightforward to analyze the average time the packets spend in the network to determine a measure for the overall transmission speed of the network.

The total throughput capacity can be measured by R_c, the critical R vale at which a continuous phase transition will occur from free state to congestion. Following [19] we define R_c through the congestion measure η

$$\eta(R) = \lim_{t\to\infty} \frac{C}{R}\frac{\langle \Delta N_p \rangle}{\Delta t}$$

where $\Delta N_p = N(t+\Delta t) - N(t)$ with $\langle ... \rangle$ indicates average over time windows of length Δt and $N_p(t)$ represents the number of data packets present in the network at time t. If $\eta(R)$ is significantly grater than zero ($\eta(R)$>0.25), it indicates a congested state of the network. Although our aim in this article is not to determine the R_c values in various cases, we will use this indicator to describe non congested ($R < R_c$, $\eta \simeq 0$) and congested cases ($R > R_c$, $\eta > 0$).

For the simulations we use a network of $n = 300$ nodes generated with a seed of 10 nodes, $m = 4$ and $\beta = -2$. The nodes are moving on the unit square.

A. The effect of position guided routing

As it has been described in Eq. 2, our model assumes that the nodes at local routing take into account the position of neighboring nodes as well. First let us analyze how this affects the efficiency of the network in the reference case when the nodes are fixed, i.e., not moving, and no reconfiguration takes place. As reference we use $C = 7$ and $\alpha = -1$, $R = 10$ in the non congested and $\alpha = 0$, $R = 20$ in the congested case. These cases result in $\eta = 0.011$ and $\eta = 1.189$ respectively.

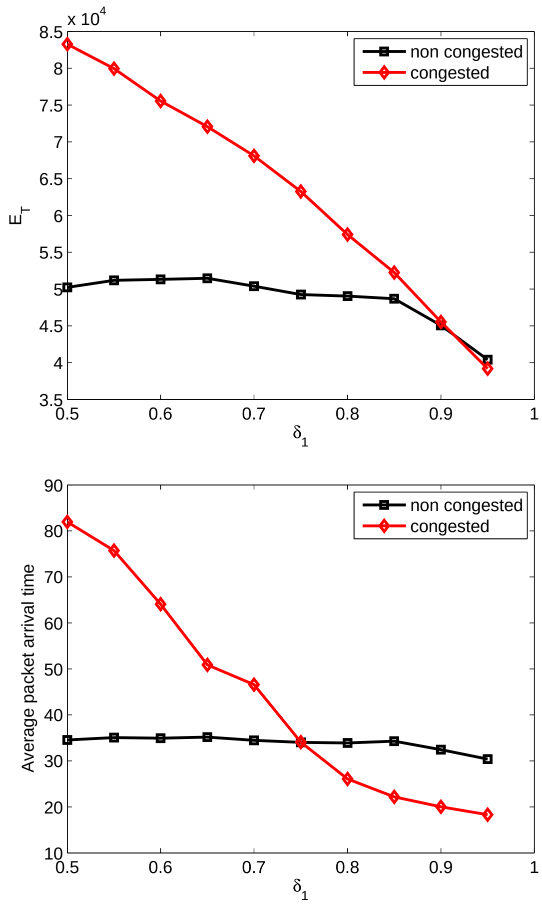

Fig. 1. Total energy consumption E_T and average packet travelling time $\bar{T}_{arr}$ as a function of δ_1, assuming $C = 7$, and $\alpha = -1$, $R = 10$ in the non congested case and, and $\alpha = 0$, $R = 20$ in the congested case. No reconfiguration.

As it can be seen in Fig. 1, position guided routing is markedly more beneficial in the congested case. In the non congested case only a small improvement can be observed in $\bar{T}_{arr}$, which approximately decreases from 35 to 31 time steps. We have to note furthermore that the case $\delta_1 = 1$ leads to deadlock situations, due to scenarios in which packets are routed to nodes who do not have connections to nodes closer to their destination position.

As shown in Fig. 2 distribution of packet traveling times shows an exponential distribution, which is modulated by the parameter δ_1. Since the differences in the non congested case are not spectacular, only the congested case is depicted.

B. Free reconfiguration

In this subsection we will assume that the reconfiguration requires no energy ($E_{RC} = 0$), or in other words, the energy

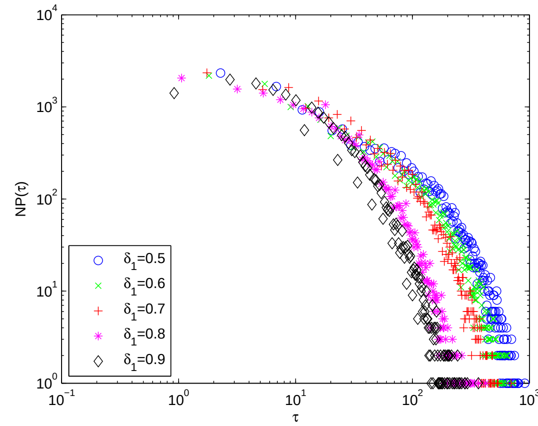

Fig. 2. The distribution of packet traveling times in the congested case for different values of δ_1.

needed for the reconfiguration can be neglected compared to the energy cost of the transmissions ($E_T = E_{TR}$).

First we demonstrate that the intuition described in II-A is correct. We assume periodic reconfiguration with time period T_r and analyze the network performance. The simulation was performed with $n^r_{seed} = 10$ for 1000 steps.

As it can be seen in Fig. 3, which depicts the results corresponding to the non congested case, as reconfiguration becomes more seldom the total transmission energy of the network grows. The energy saving of frequent reconfiguration is more significant as the velocity of the nodes increase.

As we can see in the second subfigure of 3, the average packet arrival time $\bar{T}_{arr}$ is also enhanced by frequent reconfiguration, however the speed of the nodes does not affect the values significantly. This is not surprising, since in our model the average time a packet spends in the network (the number of hops in other words) does not depend on the euclidian distance it travels. It can be clearly seen however that frequent reconfiguration is beneficial for the average packet traveling time.

In the congested case the trends are similar, however, as one may see on Fig. 4, in this case the average packet traveling time is strongly affected, and the effect is more differentiated regarding the movement speed of the agents. In this case the efficiency benefit brought by frequent reconfiguration is greater as well.

C. Reconfiguration with energy demand

In this subsection we demonstrate the results corresponding to the cases when $E_{RC} \neq 0$. We compared the total energy consumption of the system (which is the sum of transmission energy cost and reconfiguration energy cost) at a given average speed (corresponding to $v_{max} = 0.05$) in the non congested and in the congested case considering various values of E_{RC}. The results are shown in Fig. 5.

It can be seen in Fig. 5 that the total energy consumption of the system has a minimum at $T_R \neq 0$, however, the exact value of the optimum changes with E_{RC}. The curves

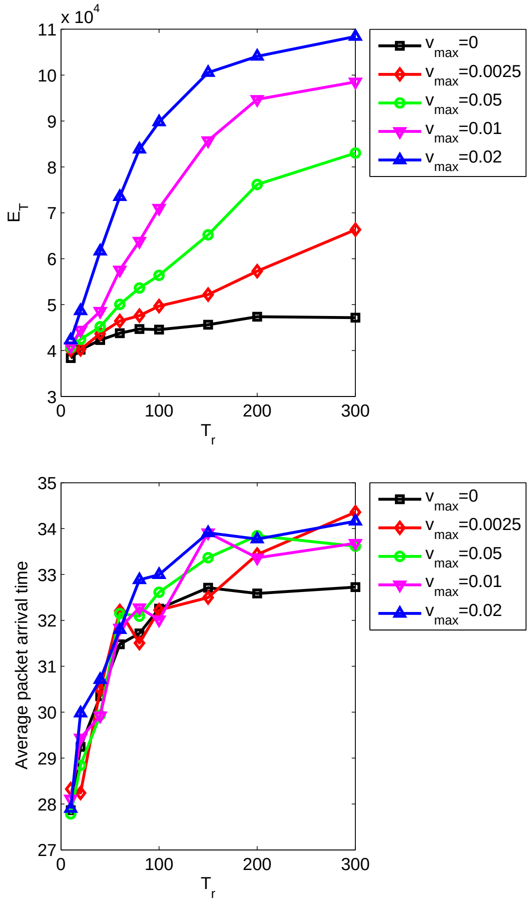

Fig. 3. Total transmission energy E_T and average packet traveling time $\bar{T}_{arr}$ as a function of reconfiguration time period T_r, assuming periodic reconfiguration and no energy cost of reconfiguration. $\alpha = -1$, $\delta_1 = 0.8$, $C = 7$, $R = 10$, no congestion.

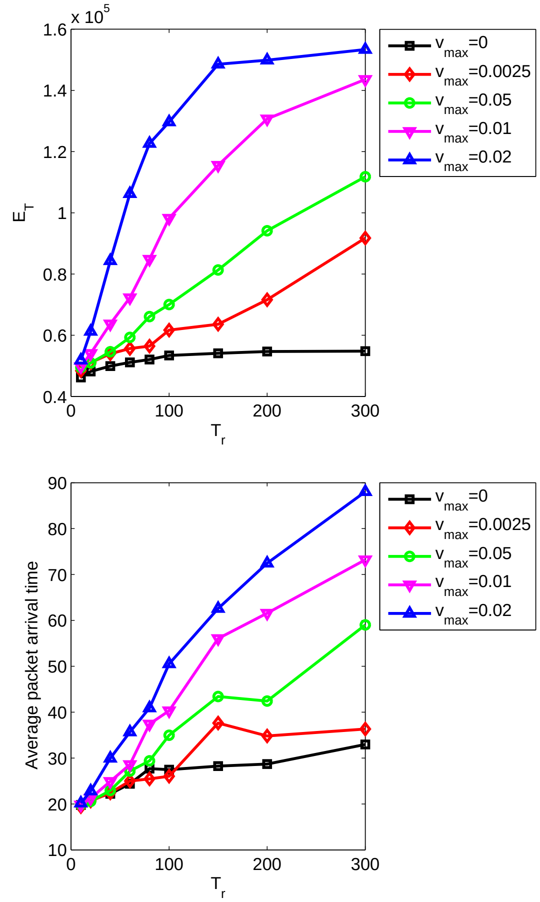

Fig. 4. Total transmission energy E_T and average packet travelling time $\bar{T}_{arr}$ as a function of reconfiguration time period T_r, assuming periodic reconfiguration and no energy cost of reconfiguration. Congested case $\alpha = 0$, $\delta_1 = 0.8$, $C = 7$, $R = 20$.

corresponding to the congested case show no significant difference in this case.

Since the energy demand of the reconfiguration does not affect the packet traveling times, it can be observed in Figs. 3, 4 and 5, that in the case of a medium node traveling speed ($v_{max} = 0.05$) and when the reconfiguration is not free but its cost is in the interval of a few thousand units, a reconfiguration period of $T_R = 60...75$ ensures energy efficient operation of the system, and quite low average transmission time of the packets. The simulation results suggest, however, that the value of such an optimum may strongly depend on the parameters of the network. Therefore, it would be desired to define algorithms which find the optimal reconfiguration interval for a given network, or trigger the reconfiguration of the system based on the actual state of the network, considering actual loads and spatial information as well.

IV. Discussion

We developed a model in which we analyze the effect of spatial information on the efficiency of local routing in scale-free networks. We improved the model to take the movement of network nodes into account. During the study we focused on the wireless interpretation of the results and in addition to packet traveling time we analyzed the energy efficiency of the system, assuming possible reconfiguration of the communication network. Our results show that utilizing spatial information enhances the network efficiency more in the congested case, and often reconfiguration is more desired if the average speed of the nodes is higher. Based on the performed simulations we guess that if the reconfiguration is not energy-free, the total energy demand of the system shows a local minimum at a certain reconfiguration frequency, which depends on the network parameters.

It is important to note that while in the current article we analyzed only the total energy demand of the whole system, the energy consumption of the individual nodes, which may be of high importance in practical applications, may significantly differ. The distribution of the transmission energy consumption of single nodes in an example case is depicted in Fig. 6, where it can be seen that as reconfiguration becomes more frequent, the variance of the distribution describing the energy demand decreases. This is not surprising, since the intuition is that high degree nodes,

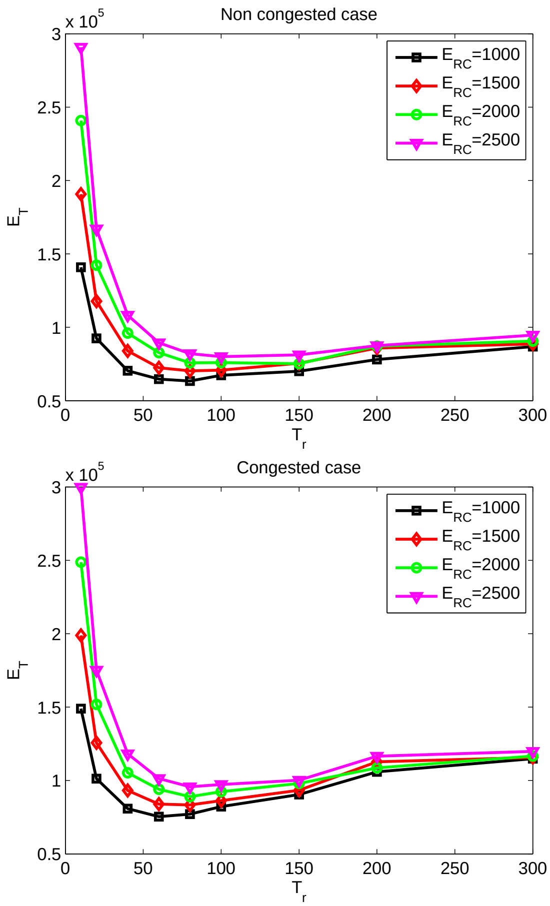

Fig. 5. Total energy consumption E_T as a function of reconfiguration time period T_r, assuming periodic reconfiguration, $\delta_1 = 0.8$ and $C = 7$. Non congested case - $\alpha = -1$, $R = 10$, congested case - $\alpha = 0$, $R = 20$.

which perform more packet forwarding, require the more transmission energy. During reconfiguration the identity of the high degree nodes change, so during the whole time period, the energy demand becomes more homogenized among the nodes.

A possible sound continuation of the proposed work would be to describe the reconfiguration in more detail, dealing with the individual energy cost of the nodes during the process.

Furthermore, as mentioned in the previous section, one possible straightforward future research direction is to take the dynamic information (actual queue length of neighboring nodes) during the process of local routing and reconfiguration into account, e.g. as proposed in [15]. The method suggested in [12] can also be analyzed in wireless environment focusing on energy efficiency. On the other hand it could be worthwhile to look for approaches and algorithms to determine the optimal time of the reconfiguration, if the reconfiguration process itself requires energy (which is a realistic assumption). In addition one may analyze how certain topological constraints (e.g. maximizing the degree of nodes during generation and reconfiguration) affect network performance. A natural future step could be scalability analysis, i.e., to increase the network size and analyze the dependency of the

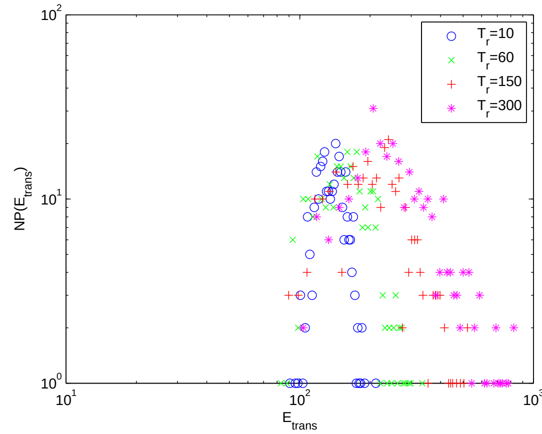

Fig. 6. Distribution of the transmission energy demand of the nodes, assuming periodic reconfiguration with various of reconfiguration time periods T_r, no congestion ($\alpha = -1$, $R = 10$), $\delta_1 = 0.8$, $C = 7$ and $v_{max} = 0.05$.

results on the number of the nodes and links.

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