Mobility Management Algorithms for Reducing Signalling Overhead in Next Generation Mobile Networks

Collection of Ph.D. Theses

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1 Introduction

A key technical challenge for next-generation mobile networks is to provide seamless access guarantees for mobile users. The seamless access and low delays can only be achieved by means of efficient mobility management to handle the frequent handovers that is experienced by a typical Mobile Terminal (MT). Therefore mobility tracking is critical for the next generation mobile networks to enable seamless handover [1]. Future mobile networks will provide ubiquitous services to a large number of MTs and the design of such networks is based on a cellular architecture that allows the efficient use of the limited available spectrum. As it is well-known, cellular communications have experienced an explosive expansion due to recent technological advances in cellular networks and cellular phone manufacturing and it is expected that they will experience even more growth in the next decade.

Upon the arrival of a mobile-terminated call, the system tries to locate the MT by searching for it among a set of base stations over the current area knowledge of the mobile. This search is called paging [2], and the set of base stations in which a mobile is paged is called the Location Area (LA). At each LA boundary crossing, MTs register their new locations through signalling in order to update the location management databases (location update procedure). MTs are free to move with a given LA without updating their location, informing the network only when crossing to a new LA. If a call is to be forwarded to the MT, the network must now page every cell within the LA to find out their exact location. Network cost is incurred on location updates and paging, the balance of these defining the field of Location Management (LM), therefore the two basic operations involved in LM are the location update procedure and paging.

A widely used static (or global) location update solution is the zone-based scheme, where the coverage area of the network is divided into the above-mentioned Location Areas, where each LA consists of a group of cells. When a MT crosses a boundary of a LA, the user updates the system with its new location information. The LAs are determined in advance based on static movement probabilities. The existing standards for location management in current mobile networks such as GSM [3], IS-41 [4] and UMTS [5] use zone-based schemes combined with different paging strategies for mobility management. Given the increasing number of MTs and transitions occurring from 2G to 3G it is crucial to improve location update and paging costs by allocating Location Areas in an optimal, implementable fashion.

2 Research Objectives

As highlighted above one of the key tasks in the field of Location Management is to find balance between the network cost caused by location update and paging operations. This tradeoff can be found in the zone-based schemes by means of efficient LA planning. Therefore the question arises, what size the LA should be for reducing the cost of paging and LU signalling (or registration signalling).

Both, increasing and decreasing the size have their own benefit. On the one hand if we join more and more cells into one LA, then the number of LA handovers will be smaller, so the number of location update messages sent to the upper levels will decrease. However in the case of large number of cells belonging to LA, an incoming call will cause lot of paging messages [6], since we must send one to every cell to find where is the mobile user inside that LA. These network-wide searches will load both the backbone and the wireless network. On the other hand if we decrease the number of cells, then we do not need to send so much paging messages, but then the number of LA changes will increase. This will cause a remarkable update overhead which puts load not only on the core (wired) network but also reduces accessible bandwidth in the mobile spectrum, including the modification cost of the location databases. The heavy power consumption of the MTs is also a major drawback of needless location updating. Therefore the overall problem in LA planning comes from the tradeoff between the paging cost and the registration cost.

Location Area planning in zone-based schemes is widely studied; these LA planning methods can be grouped into two categories. In the first group a uniform user distribution and inter-cell movement rate is assumed, and with these assumptions optimal LA planning is introduced [7], [8]. These results can not be applicable to most of the practical cases where these network properties are heterogeneous [9]. The second group consists of LA planning solutions where the network is described by a graph [10], [11] where the cells of the network are represented with the nodes, and the inter-cell movement rates with the edges of the graph. This way the LA planning is mapped to a graph partitioning problem. In [12] a LA planning scheme is introduced for covering highways where a homogeneous traffic and user density is assumed. This contribution, as papers [13] and [14] also, are dealing with the determination of the optimal number of cells in an LA, but they were not focusing on the selection of the optimal set of cells for each LA.

Instead of this, the objective of my thesis was to propose a solution to obtain the optimal partition of cells for every LA. As mentioned above, the uniform inter-cell movement rate distribution is not always realistic, therefore I present a LA planning solution for the heterogeneous mobility environment and for the homogeneous also, and this gives the real novelty of my work. In the heterogeneous case, the optimisation goal was to reduce the Location Update and the aggregated cost, while in the second case the Paging Cost is considered as a constraint; therefore the Location Update Cost is left alone in the objective function.

This two-case LA planning scheme (Thesis I) gives the input to my hierarchical network design algorithm (Thesis II), therefore these two design methods constitute an integral cellular network planning framework.

To address not only the designing aspects of a cellular network, in Thesis III novel information dissemination strategies are introduced for a non-traditional communication approach: my research interest was in developing novel information dissemination solutions for disconnected, autonomous networks, lacking any central infrastructure, to decrease the signalling overload of message forwarding. Thus beside the practical designing methods for already world widely used networks, new algorithms are presented for autonomic networks which is a cutting edge area in the field of information science, and it is believed to cause a marked shift in the way communication systems and networks are conceived. An important objective was to use a bio-inspired framework which utilizes natural selection for choosing the adequate information dissemination algorithm for different mobility environments in a self-managing mobile ad hoc network. In this framework the cooperation between the nodes can be examined, how they improve the overall parameters of the system like throughput and data age.

3 Research Methodology

Two classical approaches were used in my theses: analytical considerations and simulations. In the analytical part the cost structure was defined for the LA and hierarchy forming schemes (Theses I.-II.) and the mobile network was modelled with a graph, introducing the mathematical description of the algorithms. In Thesis III the mobility models were developed by modifying the existing group mobility models taken from the literature, adapting them to a disconnected mobility environment.

All the algorithms are implemented in the simulators together with the recently developed algorithms in these research areas, providing a useful tool for the performance evaluation of the new mobility management framework. The input of the algorithms was generated by the mobility simulator, producing a realistic cell boundary crossing (inter-cell movement rate) and incoming call database in a given mobile system, which is a good representation of the mobility patterns in real life.

4 New Results

4.1 Location Area Optimization Algorithms

THESIS 1 ([D1], 2.1-2.7, 3.1-3.4, [B1], [B2], [J1], [J2], [C1], [C2], [C3], [C4], [C5], [C7]) *I have formulated a mathematical description of the paging and location update cost functions for both a heterogeneous and a homogeneous mobility environment. I have presented for the homogeneous environment a mathematical analysis for the determination of the optimum number of cells per Location Area. For both environments I have designed Location Area forming algorithms based on the statistical probabilities of the moving directions chosen by the mobile users. I have shown analytically in special cases and in a general case by simulations that significant reduction was achieved in the amount of the signalling traffic for both scenarios.*

4.1.1 Location Area Optimization Algorithms for a Heterogeneous Mobility Environment

Most of the references related to the LA design are focused on how to determine the optimal number of cells for an LA, while in this thesis LA forming algorithms are presented which can give us effective partition of cells into LAs.

First a LA planning method is introduced for a heterogeneous mobility environment, which means the inter-cell movement rate distribution is not near uniform, not as it is assumed in the majority of LA planning schemes published earlier. Therefore the goal was to minimize the sum of the location update and paging cost, while in the near-uniform distribution case the final goal is the determination of optimum number of cells per LA for which the location update cost is minimum, with the paging cost as an inequality constraint function, which gives the novelty of this research, namely for both environments the LA structure can be optimized.

My LA planning solution uses the basic idea to group cells according to the inter-cell movement rates, in such a way to reduce the inter-LA movements of the MTs. This means that the final goal was to maximize the intra-LA traffic, because in this way the number of the LA handovers can be decreased, and therefore the total amount of administrative messages. The problem of partitioning the given set of cells into a family of disjoint subsets such that the cardinality of each subset is lower than or equal to a constraint (number of cells in a LA) and the total inter-cell movement rate between the members of each subset is maximized was found in [15] as NP-complete, with a detailed proof.

Since the time required to solve this problem grows exponentially in the size of the problem, no algorithm exists that ensures optimal results in reasonable amount of time. Therefore, techniques that offer near-optimal solutions within acceptable run times are required. An adequate approach is the use of heuristic algorithms for approximating the optimum location area configuration and later improving it with different techniques. In general case simulation examinations could be carried out to compare different LA planning solutions, analytical results could be derived for only special cases because of the complexity of the problem.

The LA planning method for a heterogeneous environment is composed of two phases: minimizing the location update cost with a heuristic algorithm (LA forming algorithm) first, and after using that basic partition as an input to a regrouping algorithm, which will reduce the aggregated cost function, So, this complex problem have to be split into two sub problems to optimize the location update cost and the aggregated cost, one after another.

I have introduced a mathematical description of the paging and location update cost function, and the aggregated cost on the end.

On the arrival of an incoming call, the network sends a paging message to every base station which belongs to the LA where the MT resides, in order to find out the called MT. So each cell in the given LA will carry all the paging traffic associated with the called MTs within that LA. In order to characterize a network configuration a Paging Cost function is defined for the l^{th} LA by which we can describe the bandwidth seized by the paging operations in a unit time interval:

$$C_{p_l} = \sum_{i=1}^{K_l} N_l \cdot \lambda_{il} \cdot B_p , \qquad \textbf{(1)}$$

where N_l is the number of cells in the given l^{th} LA, λ_{il} denotes the incoming call rate to the given i^{th} MT (number of calls in the unit time interval), B_p is the paging cost, and finally K_l is the number of MTs in the l^{th} LA.

The total paging cost for the LAs in the system in the unit time interval:

$$C_p = \sum_{l=1}^{M} C_{p_l} = \sum_{l=1}^{M}\sum_{i=1}^{K_l} N_l \cdot \lambda_{li} \cdot B_p = B_p \cdot \sum_{l=1}^{M} N_l \cdot \sum_{i=1}^{K_l} \lambda_{il} , \qquad \textbf{(2)}$$

where M is the number of LAs in the system.

I have defined also a Location Update Cost function for the network, where the location update overhead is caused by the LA boundary crossings; these inter-LA movements will generate additional location update traffic, by informing their home agents about their new location.

The Location Update Cost for the l^{th} LA in the unit time interval:

$$C_{lu_l} = B_{lu} \cdot \sum_{j=1}^{D_l} q_{jl} , \qquad \textbf{(3)}$$

where B_{lu} is the cost required for transmitting a location update message, q_{jl} is the intensity of cell boundary crossings on the j^{th} boundary (number of crossings in the unit time interval) and finally D_l is the number of the exterior cell border-lines of l^{th} LA

The total Location Update Cost for the LAs in the system:

$$C_{lu} = \sum_{l=1}^{M} C_{lu_l} = B_{lu} . \sum_{l=1}^{M}\sum_{j=1}^{D_l} q_{jl} \qquad \textbf{(4)}$$

where M is the number of LAs in the system.

The aim of the LA planning scheme is to reduce the aggregated cost function, with variable weight factors, which takes into consideration both aspects of forming LAs. The w_1 and w_2 weight factors depend on the preferences of the network designer, typically the $w_2 = H_{pref}.w_1$ and $H_{pref} \in [2,10]$:

$$\min C_{total} = \min\{w_1 \cdot C_p + H_{pref}.w_1 \cdot C_{lu}\}. \quad \textbf{(5)}$$

On the basis of the importance of paging or rather location update cost, different weights can be used, and in that way we can dynamically adjust weights to suit the actual requirements.

THESIS 1.1 *I have proposed a heuristic based Location Area designing algorithm called LAFA (Location Area Forming Algorithm) for finding the maximum weight spanning forest in the graph $G(V,E)$.*

I have shown for special cases analytically and in general case by simulations that LAFA improves the recent results in the research area by reducing the location update cost very significantly, simultaneously not increasing the average number of cells in one Location Area, keeping the paging cost on a lower level. I have shown that in the case of 5-10 cells in a Location Area the improvement in the inter Location Area traffic can reach 40-60 percents on the average.

I have modelled the mobile network with the $G(V,E)$ graph, where the cells are the graph nodes $v \in V$, and the cell border crossing directions are represented by the edges $e \in E$ of the graph. Moving direction rates can be defined to every cell, they correspond to the probabilities of the moving directions chosen by the mobile users, when they step across the cell borders. This way I have defined weights to the edges of the graph G, non negative real numbers in the range [0,1], based on the probability values, namely the weights of the edges corresponds to the cell border crossing probabilities.

I have introduced a LA designing algorithm called LAFA (Location Area Forming Algorithm) for addressing the problem of partitioning the given set of cells into a family of disjoint subsets such that the cardinality of each subset is lower than or equal to a constraint (number of cells in a LA) and the total inter-cell movement rate between the members of each subset is maximized. Since this problem is NP-complete [15], LAFA is a heuristic algorithm for obtaining an effective location area configuration, by finding the maximum weight spanning forest of graph $G(V,E)$.

This means LAFA is dividing the graph $G(V,E)$ into subgraphs $G_i(V,E)$, in such a way to find the maximum spanning forest of graph $G(V,E)$, where the components of this maximum spanning forest are the maximum weight spanning trees of the correspondent $G_i(V,E)$ subgraphs, while the number of nodes in each subgraph is lower than or equal to a constraint and also introducing a special stopping rule.

I have analytically proven that in special cases LAFA improves the performance of a recently published significant LA forming scheme, the Traffic-Based Static Location Area Design (TB-LAD) [15] by introducing a distributive LA forming method. I have conducted simulations to analyze the performance of the proposed LAFA and the TB-LAD in a rural and an urban mobility environment. I have concluded that:

- for the rural environment by increasing the maximum number of cells which can be included into one LA (namely the $N_{\max}$) the LAFA decreases the Location Update Cost significantly compared to TB-LAD, keeping the Paging Cost on a lower level. In the cases of 5-10 cells for an upper bound per LA, my new scheme reduces the inter-LA traffic by 40-60 percents on the average (Figure 1).
- for the urban environment the LAFA also decreases remarkably the Location Update Cost compared to TB-LAD, without increasing the paging signalling load. The decrease is very significant in the interval of five to eleven cells. In the interval between 12 and 15, it does not mean that by increasing the number of cells the Location Update Cost does not decrease significantly, but the equation of LAFA is not satisfied, therefore the LAFA stops on a smaller number of cells per LA than the upper bound. The TB-LAD is always increasing the number of cells per LA till the upper bound; therefore it is producing a higher Location Update Cost for a higher number of cells per LA, which will cause a higher Paging Cost also (Figure 2).

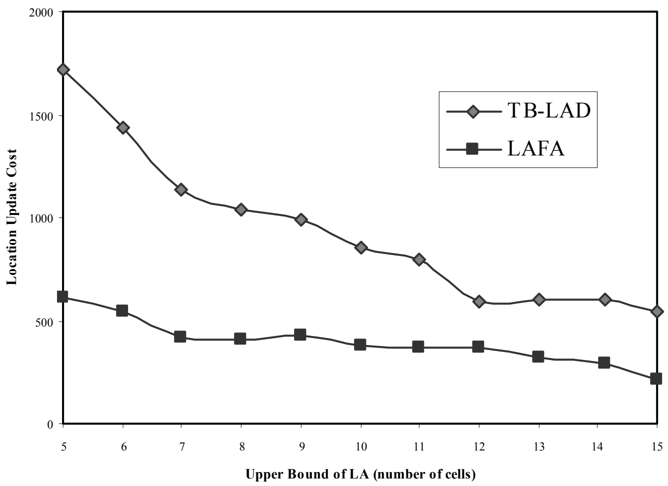

Figure 1 The Location Update Cost in rural environment for the TB-LAD and the LAFA partition

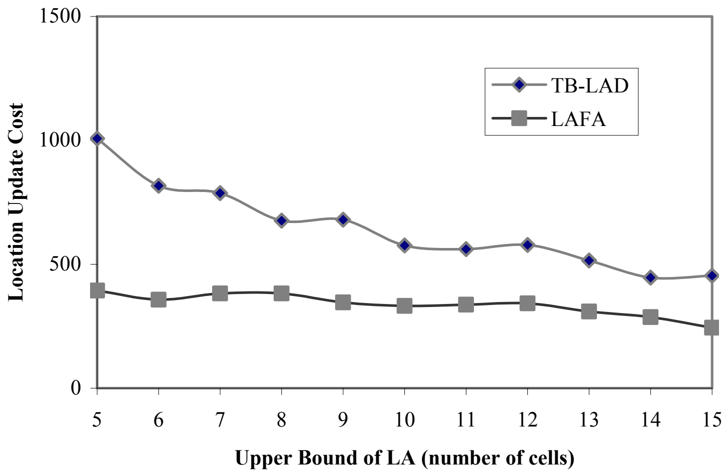

Figure 2 The Location Update Cost in urban environment for the TB-LAD and the LAFA partition

THESIS 1.2 *I have developed a Location Area forming algorithm called CEREAL (Cell Regrouping Algorithm) for improving the performance of LAFA in the terms of the aggregated cost function. I have revealed by extensive simulations that the CEREAL algorithm is outperforming the LAFA in terms of the aggregated cost.*

The proposed CEREAL algorithm is minimizing the aggregation cost function by transposing the cells into adjacent Location Areas, what will result in a significant reduction of location update and paging costs. I have characterised the effectiveness of the CEREAL algorithm using total cost metric, the sum of the location update and paging cost versus the value of parameter K which was employed in the LAFA. The parameter K can be dynamically modified, depending on the model which is deployed. It changes in the (0,1) interval, as it converges to 1, the size of the LA-s are decreasing, which will mean that the Location Update Cost will increase significantly as the parameter K increases, while on the Paging Cost it will have a contrary effect.

I have carried out simulation studies to examine what will happen if the CEREAL algorithm is employed on the initial partitioning obtained by the LAFA. The aggregated cost was measured (C_{total}), versus the value of parameter K which was employed in the LAFA. I have concluded that:

- for the rural environment in the case of the aggregated cost the effect of increasing the value of parameter K is just the opposite of that in case of the Location Update Cost. The reason is that by increasing the value of parameter K, the size of the LA-s is getting smaller, so the Paging Cost is decreasing significantly. In this case CEREAL is outperforming the LAFA partitioning method significantly, for $K \in [0.1, 0.4]$ and $K \in [0.6, 0.7]$ over 40% (Figure 3).
- for the urban environment the CEREAL decreases the amount of the aggregated cost by 30-40% compared to LAFA, and it does not depend on the value of parameter K (Figure 4).

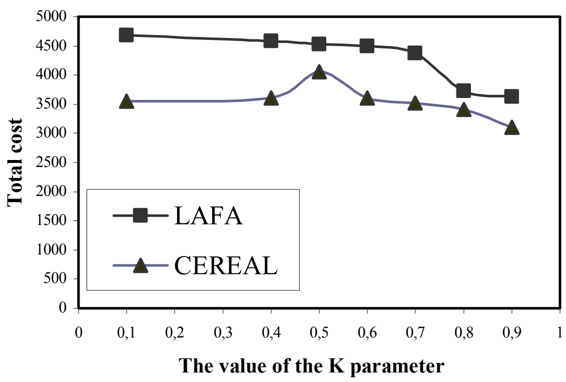

Figure 3 The aggregated cost versus the value of parameter K (rural)

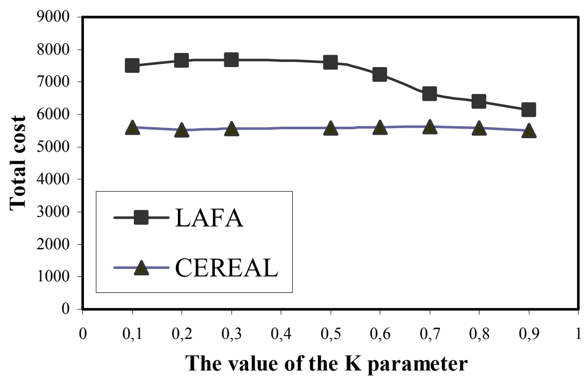

Figure 4 The aggregated cost versus the value of parameter K (urban)

Depending on the objective we can deploy only the LAFA algorithm or followed by the CEREAL algorithm. If we want to decrease the Location Update Cost, the LAFA is the solution, however if we want to decrease the aggregated cost, we need to employ after the LAFA the CEREAL algorithm also.

4.1.2 Location Area Optimization Algorithms for a Homogeneous Mobility Environment

As highlighted above the novelty of my contribution to LA planning is that beside these LA planning methods are more effective than the earlier introduced schemes, they can be applicable for both mobility environments, for heterogeneous and homogeneous network usage (for non-uniform and near-uniform inter-cell rates also).

While in the previous section a LA planning method was introduced for a heterogeneous mobility environment, therefore the goal was to minimize the Location Update and aggregated cost, I gave also a solution for a near-uniform inter-cell rate distribution case, where the final goal is the determination of the optimum number of cells per LA for which the Location Update Cost is minimum, with the Paging Cost as an inequality constraint function. The Paging Cost was limited, because if the stopping rule of LAFA would be applied for near-uniform inter-cell rates, all the cells will be included into one LA, not considering the capacities of the cellular network, since the paging capacities of base stations and switching centres should not be exceeded. Therefore the goal is to reach the minimum value of the Location Update cost, by calculating the optimal number of cells per LA from the paging constraint function and using the LA planning algorithms to obtain an effective grouping of cells into LAs.

This LA forming process contains two phases, first a greedy algorithm (GREAL) is adopted which forms a basic partition of cells into LAs, and then a simulated annealing based algorithm (SABLAF) is applied for getting the final partition. The same realistic mobility environment simulator was used as in Thesis 1.1 and 1.2, for the generation of the algorithm input metrics (cell boundaries crossing and incoming call statistics).

THESIS 1.3 *I have derived a fluid flow based analytical model for the movement of Mobile Terminals among the Location Areas for a homogeneous mobility environment. The main features of the model are the definition of the perimeter of a Location Area and the number of boundary cells, and finally the location update cost and the paging constraint. Based on the model I have derived a method to find the optimum number of cells per Location Area for which the location update cost is minimal and the paging constraint is satisfied.*

Every time when a MT crosses a cell boundary which is a LA boundary also, a registration process is initiated, a Location Update message is sent to the upper level (home agent or gateway). Therefore the intra-LA boundary crossing cost is negligible, and this handoff cost should be not considered in the Location Update Cost. Hence the number of cells located on the boundary of the k^{th} LA (the set of the boundary cells is a subset of N_k) and the proportion of the boundary cells perimeter which contributes to the k^{th} LA perimeter was needed to be determined.

By defining the equations for the number of boundary cells (N_{p_k}) and the average proportion of the boundary cell perimeter in the k^{th} LA perimeter ($\delta_{p_k}(N_k)$, I have derived the expression for the perimeter of the k^{th} LA:

$$P_k = \kappa \cdot \sqrt{N_k} \cdot P_c \cdot \left(a + b \cdot {N_k}^{\eta-1}\right) \qquad \textbf{(6)}$$

By substituting the values of ρ and P_k in the outflow rate of the fluid flow model (the outflow rate will be equal with the number of crossing the k^{th} LA boundary):

$$R_{out} = \left(\frac{v \cdot \frac{K}{N_k \cdot S} \cdot \kappa \cdot \sqrt{N_k} \cdot P_c \cdot \left(0.333 + 0.309 \cdot N_k^{-0.425}\right)}{\pi} \right) \quad \textbf{(7)}$$

Using the above introduced equations I have defined the Location Update Cost for a unit time interval:

$$C_{LU_k} = B_{LU} \cdot v \cdot K \cdot \kappa \cdot P_c \cdot \left(\frac{0.333 \cdot N_k^{-0.5} + 0.309 \cdot N_k^{-0.925}}{\pi \cdot S} \right) \quad \textbf{(8)}$$

Considering the paging capacities of a cellular network, I introduced a paging constraint for the k^{th} LA:

$$C_{P_k} = B_P \cdot N_k \cdot K_k \cdot \lambda < C_k \quad \textbf{(9)}$$

I gave a solution to the problem to find the optimum number of cells per LA for which the Location Update is minimal and the paging constraint (C_k must not be exceeded) is satisfied, the maximum value (N_{opt}) of N_k can be calculated:

$$P(\lambda < \frac{C_k}{B_P \cdot N_k \cdot K}) = 1 - e^{-\gamma} \quad \textbf{(10)}$$

Substituting the calculated value of N_{opt} will give the minimum of the Location Update Cost. This calculated N_{opt} is used as an input for the GREAL and SABLAF algorithm.

THESIS 1.4 *I have developed a Location Area forming algorithm for a homogeneous mobility environment called SABLAF (Simulated Annealing based Algorithm). I have shown that for the urban and rural mobility environment the SABLAF algorithm improves the performance of the recent solutions in the research area, by reducing the location update cost.*

I have modified the LAFA algorithm to be useable for a near-uniform inter-cell movement rate distribution, introducing a LA forming algorithm called GREAL (Greedy Algorithm), which produces the initial LA partitions for the SABLAF algorithm. GREAL gives a division of graph $G(V,E)$ into subgraphs $G_i(V,E)$, finding the maximum spanning forest of graph $G(V,E)$. The components of the maximum spanning forest are the maximum weight spanning trees of the correspondent $G_i(V,E)$ subgraphs, while the number of nodes in each subgraph is lower than or equal to a constraint (N_{opt}); but there is no special stopping rule like in LAFA, only the maximal number of cells per LA constraint will stop the forming of a single LA. In my solution the simulated annealing based algorithm (SABLAF) here finds a basic LA partition formed by the GREAL algorithm, with the handover rate database among the cell pairs.

I have compared the performance of the GREAL, SABLAF and the TB-LAD solution by using the two mobility environments (rural and urban).
I have concluded that:

- for the rural environment the GREAL algorithm can decrease the Location Update Cost compared to the TB-LAD solution, but only the SABLAF algorithm finds the best solution for every value of the maximal number of cells per LA. For the calculated value of $N_{opt} = 12$, the Location Update Cost reaches the minimum value using the simulated annealing based technique (Figure 5).
- for the urban environment in the initial stages (where the value of maximal number of cells per LA is less than 5) SABLAF algorithm almost always accepts the partition formed by the GREAL algorithm or a very similar partition, but as the number of cells increases, the SABLAF is outperforming the other two solutions significantly. For the calculated value of the $N_{opt} = 14$ (higher value than for the rural environment, because of the cell sizes and numbers) the SABLAF algorithm gives again the minimum of the Location Update Cost (Figure 6)

It can be summarized, that for both mobility environments the SABLAF algorithm gives the best results, decreasing the Location Update Cost almost for 50% more effective than the TB-LAD solution, and for approximately 20% more than the GREAL algorithm.

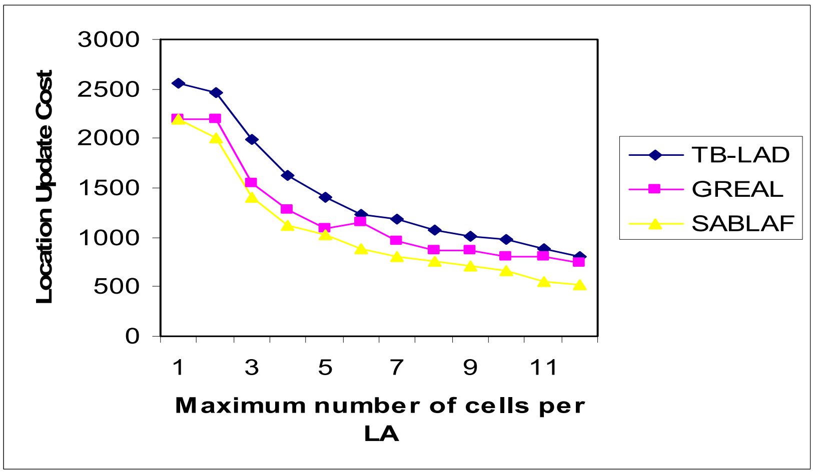

Figure 5 The Location Update Cost in rural environment

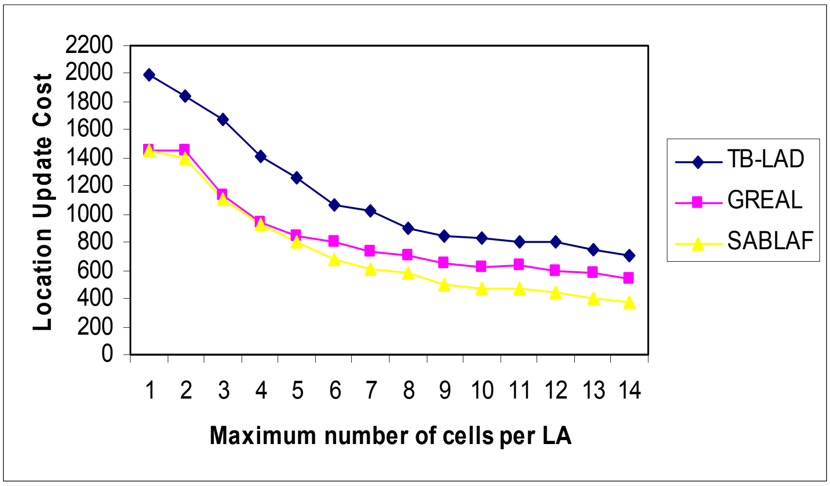

Figure 6 The Location Update Cost in urban environment

4.2 Network Design Algorithm for Optimizing the Upper Hierarchical Mobile Structures

THESIS 2 (([D1], 4.1-4.6; [J3], [C11]) *I have proposed a cost structure to measure the cost caused by the location update and packet delivery procedures in a Proxy Agent Architecture. I have derived a model for the optimal tree hierarchy of a Proxy Agent Architecture as a probability tree introducing the average distance of the Access Routers from the top router. I have proposed a hierarchy designing algorithm called HIENDA (Hierarchical Network Design Algorithm), which gives a probability tree where the average distance* $\mathrm{E}(L)$ *of the Access Routers from the top router is minimal. I have shown by simulations that the HIENDA improves the recent results in the research area in terms of location update cost, at the same time keeping the packet delivery cost on a low level.*

Mobile IPv6 [16] is an extension to IP to manage the mobile node's (MN, term used in IP) mobility, but not capable of supporting real-time handovers. A solution is to make Mobile IPv6 responsible for macro-mobility, and to have a separate protocol to manage local handovers inside micro-mobility domains. One of the most significant micro-mobility solutions to reduce the number of signalling messages to the home network and also to reduce the signalling delay is the Hierarchical Mobile IPv6 (HMIPv6) [17]. The basic idea of this hierarchical approach is to use domains organized in a hierarchical architecture with a mobility agent on the top of the domain hierarchy. HMIPv6 utilizes a hierarchical network of routers and introduces a new Mobile IPv6 node, called the Mobility Anchor Point (MAP). It can be located at any level in a hierarchical network of routers, including the Access Router (AR), which is the Mobile Node's default router, aggregating the outbound traffic of MNs. The deployment of the MAP concept will further reduce the signalling load over the air interface produced by Mobile IPv6, by limiting the amount of Mobile IPv6 signalling outside the local domain.

The problem is that the RFC 4140 or other drafts do not address the realization of the hierarchical structure in detail during the network design. Several important questions arise: what kind of principles must be used to configure the hierarchical levels, how to group cells under a given Access Router, and in which hierarchical level is advisable to implement the MAP function. The MNs traffic load and mobility may vary; therefore a fixed structure is lack of flexibility. I have already given in Thesis I mobility management solutions for Location Area domain forming which are capable of reducing the signalling overhead caused by the cell boundary crossing. Therefore with these Location Area planning algorithms, we can obtain the optimal partition of cells for a given Access Router, which will represent a Location Area router.

A key issue is how to group these Access Routers on the next level of hierarchy, and on which level of hierarchy to implement the MAP functionalities, actually how many Access Routers should be beneath a MAP within a domain. The number of ARs under a MAP is very critical for the system performance. I gave hierarchy designing principles which can be used in Proxy Agent Architectures in general, also in HMIPv6 which is a member of this micro-mobility protocol group.

If the location registration message flow in a Proxy Agent Architecture (the terminology of the Hierarchical Mobil IPv6 is used) is examined between the home network and the MN covered by a MAP function, the cost of a MN movement from one subnet to another can be calculated in a following way:

$$C_{LU} = 2 \cdot T_{HA-MAP} + 2 \cdot T_{MAP-AR} + 2 \cdot T_{AR-MN} + p_{HA} + 2 \cdot p_{MAP} + 2 \cdot p_{AR}, \qquad \textbf{(11)}$$

where T_{HA-MAP}, T_{MAP-AR}, T_{AR-MN} are the transmissions costs of location update between the Home Agent (HA), MAP and AR, p_{HA}, p_{MAP}, p_{AR} are the processing costs of location update at the HA, MAP and AR.

If a MN is changing an AR, but not a MAP, the Home Agent will not be informed about this local change, therefore a localized location update cost will be produced:

$$C_{LUl} = 2 \cdot T_{MAP-AR} + 2 \cdot T_{AR-MN} + p_{MAP} + 2 \cdot p_{AR}. \qquad \textbf{(12)}$$

The transmission cost is proportional to the distance between the source and the destination in terms of the number of hops packets travel (n_{S-D}) (with a proportionality constant of K_T), while the transmission cost of the wireless link is usually higher, than that of the wired link (μ times higher). If we consider that only an ε fraction of the MNs subnet changes (then the MN moves from an AR to another) is a MAP change, then the total amount of the registration signalling cost can be expressed as:

$$C_{LUtotal} = (1-\varepsilon) \cdot q \cdot C_{LUl} + \varepsilon \cdot q \cdot C_{LU} \qquad \textbf{(13)}$$

$$C_{LUtotal} = q \cdot \left(2 \cdot \varepsilon \cdot n_{HA-MAP} \cdot K_T + 2 \cdot n_{MAP-AR} \cdot K_T + 2 \cdot \mu \cdot n_{AR.-MN} \cdot K_T + \varepsilon \cdot p_{HA} + (1+\varepsilon) \cdot p_{MAP} + 2 \cdot p_{AR}\right) \qquad \textbf{(14)}$$

where q is the number of AR changes (or LA boundary crossing) in the system in the unit time period.

In Mobile IP every IP packet destined for the MN is first intercepted by the HA and then tunnelled to the MAP where MN is registered, forwarding the packet to the current serving AR of the MN. This will produce an additional transmission and processing cost:

$$C_{PD} = \sum_{k=1}^{N} \theta_i (D_{HA-MAP} + D_{MAP-AR} + h_{HA} + h_{MAP}), \qquad \textbf{(15)}$$

where N is the number of the MNs in the system, θ is the number of arriving packets to the MN in the unit time period, D_{HA-MAP}, D_{MAP-AR} are the transmission costs of packet delivery and finally h_{HA}, h_{MAP} are the processing costs of packet delivery.

Similar to the location registration cost, the transmission cost is proportional to the number of hops packets travel between the source and the destination, with a K_D proportionality constant for packet delivery:

$$C_{PD} = \sum_{k=1}^{N} \theta_i (n_{HA-MAP} \cdot K_D + n_{MAP-AR} \cdot K_D + h_{HA} + h_{MAP}). \qquad \textbf{(16)}$$

THESIS 2.1 *I have derived the following cost functions, which can measure the signalling traffic flow in Proxy Agent Architectures:*

- *Localized Update Cost*
$$C_{LUl} = 2 \cdot T_{MAP-AR} + 2 \cdot T_{AR-MN} + p_{MAP} + 2 \cdot p_{AR} \quad \textbf{(12)}$$
- *Total Location Update Cost*
$$C_{LUtotal} = q \cdot \left(2 \cdot \varepsilon \cdot n_{HA-MAP} \cdot K_T + 2 \cdot n_{MAP-AR} \cdot K_T + 2 \cdot \mu \cdot n_{AR.-MN} \cdot K_T + \varepsilon \cdot p_{HA} + (1+\varepsilon) \cdot p_{MAP} + 2 \cdot p_{AR}\right) \quad \textbf{(14)}$$
- *Packet Delivery Cost*
$$C_{PD} = \sum_{k=1}^{N} \theta_i (n_{HA-MAP} \cdot K_D + n_{MAP-AR} \cdot K_D + h_{HA} + h_{MAP}) \quad \textbf{(16)}$$

THESIS 2.2 *I have derived a probability tree based model for the tree hierarchy in a Proxy Agent Architecture for a given source of Access Router handover rates.*

The Proxy Agent Architecture probability tree is a finite tree-graph and for every node of the tree-graph a non-negative number is assigned, based on the next definitions:

- A probability tree is a labelled tree, in which each internal node represents a variable and each leaf node represents a probability value.
- The probability of the root node is equal to 1.
- Probability of every node is equal with the sum of the probabilities of the belonging sub-tree (a tree originating from this node).
- The probabilities of the terminal nodes are calculated on the base of the AR handover rates, the ratio of the given AR handover and the total amount of handovers in the network.

The Path Length Lemma from Huffman coding is applied to calculate the average distance $\mathrm{E}[L]$ of the ARs (terminal nodes) from the top router (root node), where L is a probability variable of the route length, and it is equal to the sum of the probabilities assigned to the non-terminal nodes, considering the top router as a non-terminal node too.

$$P_{root} + P_{I1} + P_{I2} + \ldots + P_{IR} = \sum_{i=1}^{T} n_i \cdot P_H(h_i) = \mathrm{E}(L) \quad \textbf{(17)}$$

where R is the number of the interval routers, T is the number of ARs, n_i is the number of hops between the ARs and the top router, and $P_H(h_i)$ is the AR handover rate probability distribution.

THESIS 2.3 *I have proposed a hierarchy designing algorithm called HIENDA (Hierarchical Network Design Algorithm), which gives a probability tree, where the average distance $\mathrm{E}(L)$ of the Access Routers from the top router is minimal. I have shown that the HIENDA algorithm outperforms the Multi-Level HMIPv6 solution in point of the location update and total signalling cost, simultaneously keeping the packet delivery cost low.*

The signalling cost is proportional to the number of handovers among different hierarchical entities; therefore the signalling cost can be reduced by designing a hierarchy for a Proxy Agent Architecture in a way that the ARs (or the LAs assigned to them) belonging to one hierarchical entity have the highest boundary crossing rates among each other. In this way the signalling messages will only be sent one level up in the hierarchy, and not to the top of the hierarchy. Accordingly the main goal of the HIENDA algorithm is to reduce the overall cost by minimizing the number of the AR changes which are at the same time MAP changes also. Therefore it is joining those ARs which have a high handover rate among each other into one MAP domain, hence the number of MAP domain changes will decrease significantly. A modified Huffman-algorithm is used for this purpose, which is reducing the number of hops the packets are travelling through, in this way the Location Update Cost can be minimized.

Therefore the HIENDA algorithm gives a probability tree where the average distance $\mathrm{E}(L)$ of the terminal nodes from the root node is minimal for a given AR handover rate probability distribution ($P_H(h_i)$) and given number of terminal nodes (T). This means the number of hops packets travel is minimal, in this way we can minimize the Location Update Cost, simultaneously keeping the Packet Delivery Cost low by the MAP deployment, obtaining a fair tradeoff between the two costs.

I have designed a simulation examination scenario for comparing the performance of the HIENDA algorithm with a hierarchy designing solution, the Multi-Level HMIPv6 [18]. For the generation of the mobility patterns I have used the mobility environment simulator introduced in Thesis I. Also the LA forming process was performed by the LAFA and CEREAL algorithms described in Thesis I. By employing these two algorithms the input for the HIENDA algorithm was created, adjusting the cell groups to the given ARs.
I have concluded that:

- in the case of $S = 2$ (when two terminal nodes were aggregated in each step of the algorithm), the HIENDA algorithm outperforms the Multi-Level HMIPv6 scenario in terms of location update cost (Figure 7).
- when three nodes are aggregated in each step of the hierarchy building, the difference gets significant; the hierarchical structure created by the HIENDA algorithm is producing only half of location update messages that the Multi-Level HMIPV6 does.
- in the terms of Total Signalling Cost in the function of S, the HIENDA is outperforming the Multi-Level solution (Figure 8)

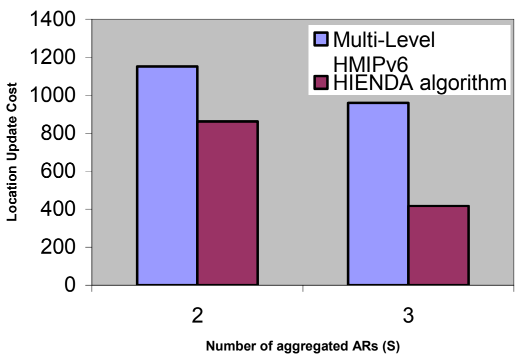

Figure 7 The Location Update Cost for the two hierarchical structures

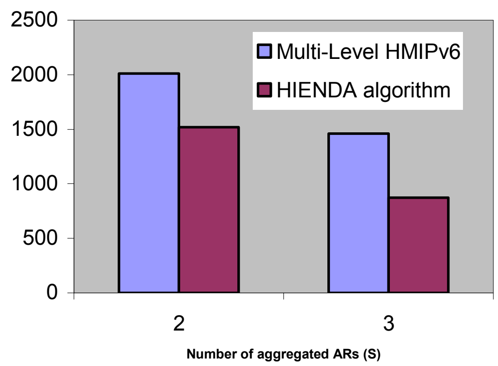

Figure 8 The Total Signalling Cost for the two hierarchical structures

4.3 Overhead Reducing Information Dissemination Strategies for Disconnected Mobile Networks

THESIS 3 (([D1], 5.1-5.7; [B3], [C6], [C8], [C9], [C10], [C12]) *I have developed two novel information dissemination strategies (MIOBIO, Multi-Message SBA) for disconnected mobile networks. I have shown that both of the new algorithms outperform recent contributions in the terms of service coverage and overhead values. I have introduced a novel approach to use an evolution based decision mechanism which utilizes natural selection for choosing the adequate information dissemination algorithm for different mobility environments in a self-managing mobile ad hoc network.*

In Thesis I and II effective network designing algorithms were introduced for signalling load optimization, in a traditional, fully-connected communication environment. As I wish to give planning principles for the next generation mobile networks, another way of communication should be envisaged too, due to the spreading of concepts about autonomic and self-organizing, disconnected networks.

Therefore a totally different, lateral thinking was needed in this research area of my Theses, to investigate how overhead of information dissemination can be decreased in a disconnected network architecture where highly mobile nodes form the network. The overhead can be defined in such networks as the overall sum of all the not useful data messages, which are called duplicates (they do not provide any new information for the nodes, which receive it) and the signalling messages needed for the algorithm operations.

THESIS 3.1 *I have proposed a novel information dissemination algorithm for a disconnected mobile network called MIOBIO (Modified InfOrmation Dissemination Protocol for BIOlogically Inspired autonomic Networks and Services). By means of extensive simulations I have shown that MIOBIO has the best overhead values for a high delivery ratio among the recent contributions.*

To eliminate the drawbacks of the earlier introduced information dissemination algorithms, a quite different approach is presented by me, the MIOBIO algorithm. It uses a simple 3-stage handshake to discover neighbours that are interested in one of the carried messages. The goal of the protocol is to reduce unnecessary load of neighbouring nodes by duplicate or unneeded data. One of the most useful properties is the limited overhead - no unnecessary data message is sent. With the 3-stage handshake we do not need to broadcast every time. The first and second steps use short control messages (advertisement and request messages); the broadcasting of the data only happens in the third step. Therefore the energy needed for communication can be reduced, because the node sends only short advertisement messages (which message should be processed by all the nodes in the communication range), and all the data will be sent only in one case: if a node needs it. The MIOBIO applies the Adaptive Periodic Flood (APF) for sending the advertisement messages. APF is a simple controlled flood protocol, which broadcasts messages periodically, and increases this period when a duplicate arrives. To combine the benefits of the two algorithms (APF and IOBIO), MIOBIO uses the APF protocol to decrease the amount of duplicate ADV messages, and uses the original IOBIO handshake to decide when data messages have to be sent.

I have conducted a simulation study using the BIONETS simulation tool [19] to examine the performance of the MIOBIO, comparing it with the recently developed algorithms, which are the best available dissemination methods published for a disconnected mobile environment: Generic Self-Pruning [20], SBA [21], Hypergossiping [22]. These algorithms were chosen after an extensive study of the surveys about data dissemination algorithms, covering a large set of different dissemination types, drawing a conclusion that the three algorithms mentioned above give a very good all-around solution that performs well in a disconnected mobile environment. A very important parameter for the performance of the algorithms is the overhead, this redundancy metric shows in average how many duplicates were received for one useful message.

I have concluded that in the case of overload MIOBIO is the clear winner, if we consider that Hypergossip produces a little bit smaller overhead, but its delivery ratio is the worst among the five algorithms, therefore it can not reach the majority of the nodes (Figure 9).

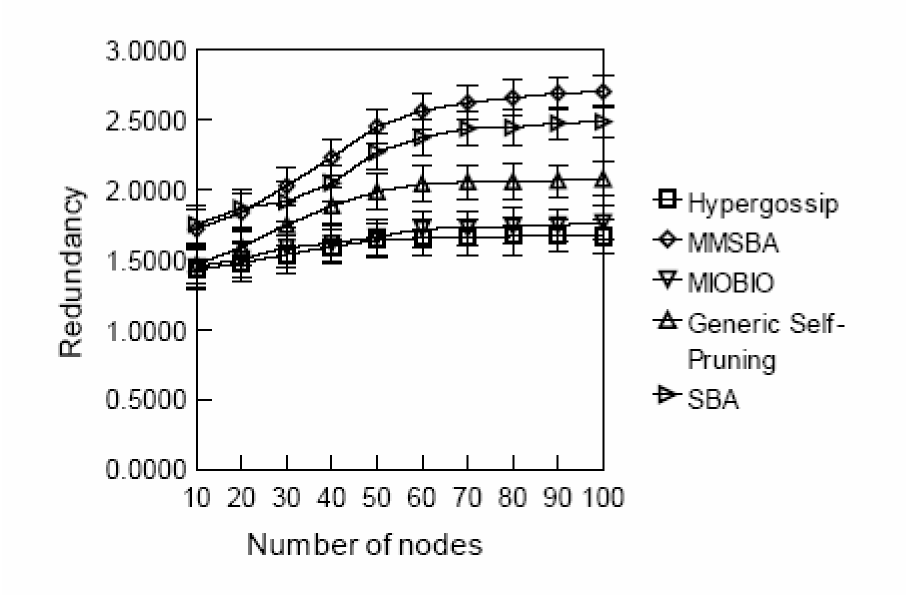

Figure 9 The overhead of the simulated algorithms

THESIS 3.2 *I have proposed a novel information dissemination algorithm called MMSBA (Multi-Message Scalable Broadcast), which is an improvement of the SBA algorithm giving a generalized mechanism for a multi-message case. I have shown that the MMSBA provides the best service coverage among the recent contributions.*

The MMSBA is a self-pruning algorithm; it requires 2-hop neighbour information and the last sender ID in the broadcasted packet. When a node v receives a broadcasted packet from a node u it excludes the neighbours of u, $N(u)$ from the set of his own neighbours $N(v)$. The resulting set $B = N(v) \setminus N(u)$ is the set of the potentially interested nodes. It is also one of the algorithms that have an explicit Random Assessment Delay (RAD) mechanism. The maximum RAD is calculated by the $\left(\frac{d_v}{d_{\max}}\right) \cdot T_{\max}$ formula, where $d_v = |N(v)|$ and $d_{\max}$ is the degree of the node with the largest degree in $N(v)$. Nodes choose the time of transmission uniformly from this interval. This ensures that nodes with higher degree usually broadcast before nodes with fewer neighbours.

The algorithms that do not take partitioning into account, like Scalable Broadcast Algorithm (SBA) and Generic Self-Pruning, perform poorly in disconnected environments. These kind of algorithms decide to rebroadcast a message only once, when it is first received. If there are no more nodes in transmission range when the last message is sent, the dissemination stops. Unfortunately, when a new node arrives into the transmission range, there is no event that can trigger a retransmission. To solve this problem, the SBA algorithm was improved, because it is computationally simple, and proved to be robust by many papers.

It also gives a nice way to generalize its mechanism to the multi-message case. My modified algorithm, the Multi-Message SBA (MMSBA) may trigger a RAD not only on the first reception of a message, but on any event that changes the local neighbourhood information. Every time a HELLO message is received, MMSBA updates his neighbour list. When the number of interested nodes exceeds zero, MMSBA starts the RAD. The RAD works exactly the same way as in SBA, therefore every time we receive a HELLO message from another node, we will put him again on the list of interested nodes, even if the broadcast message was already sent to him. This problem is not present in the original SBA, as nodes broadcast the message at least once, when it is first received. To overcome this problem, the nodes include the list of messages they have already received in their HELLO packets. This also gives a feedback to MMSBA if a broadcast message was lost during transmission. The new method allows MMSBA to handle many messages independently.

I have evaluated the performance of the MMSBA algorithm, comparing it with the information dissemination algorithms introduced in the Thesis 3.1 simulation study. I have shown that MMSBA provides the best service coverage; in the given time period the MMSBA reaches the highest proportion of the mobile nodes, outperforming the other four algorithms (Figure 10).

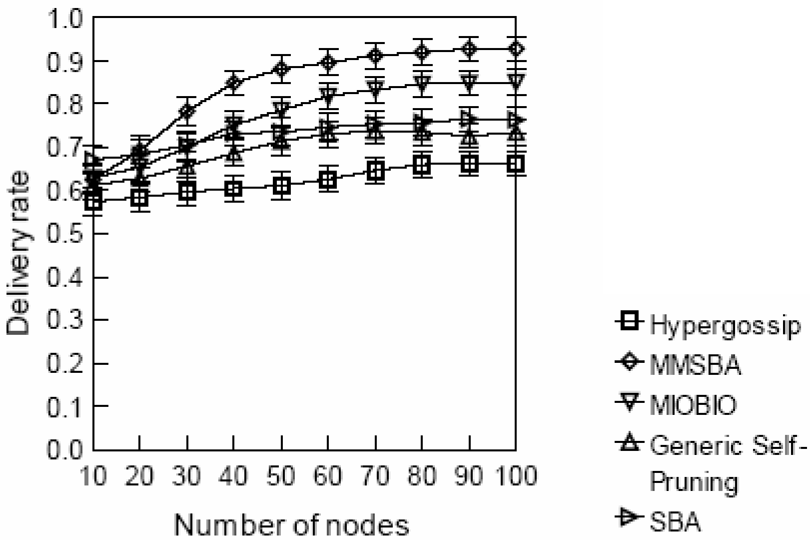

Figure 10 Delivery ratio of the simulated algorithms

THESIS 3.3 *I introduced a novel framework based on natural selection for choosing the adequate information dissemination algorithm for different mobility environments in a self-managing disconnected mobile network. I have shown that by introducing cooperation between nodes the overall parameters of the system like throughput and data age can be improved.*

While there are a huge number of message forwarding algorithms described in the literature, the environment is changing so rapidly that there is no hope for choosing a theoretically optimal algorithm. Therefore I introduced a biologically inspired solution based on the phenomena of natural selection. The individuals with the highest fitness will reproduce faster than the less fit ones. The designer chooses the fitness function so that the species with good performance will get higher fitness scores. An important benefit is that there is no central fitness evaluation; every decision is made locally in the nodes, reducing the overhead generated by the performance feedback. I have chosen the best performing algorithms based on the measurements introduced above to compete in this framework, which were the MIOBIO and MMSBA.

APF was also selected like a competitor algorithm to check what will be the impact on natural selection if a too "aggressive" algorithm is also competing with the more complex and moderate algorithms.

Simulations were carried out to analyze the effect of cooperation on the performance of the algorithms. During these measurements the cooperation level of the algorithms was changed in the simulator, called the cooperation bonus divisor, namely the ratio of the bonus points obtained by sending/receiving a useful message.

I have concluded that:

- when the cooperation level is higher, then the entire system has better performance measures (Figure 11, higher values on the horizontal axis indicate less motivation for cooperation).
- by motivating the nodes to cooperate, the average data ages decreases, which will provide the users up-to-date information (Figure 12).

In other words, the "greedy, spamming" algorithms such as flooding can be regulated this way. In this case for instance, a flood with an appropriately large back off period can survive, but a greedy one can not.

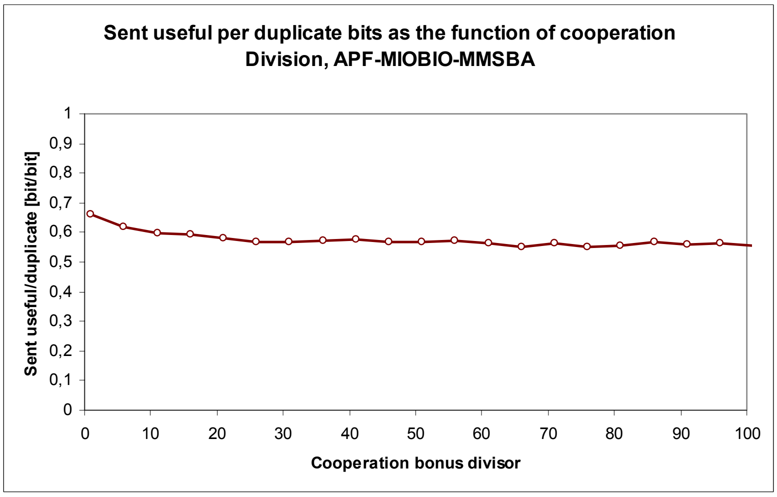

Figure 11 Sent useful/duplicate bits in function of the cooperation bonus divisor (APF/MIOBIO/MMSBA)

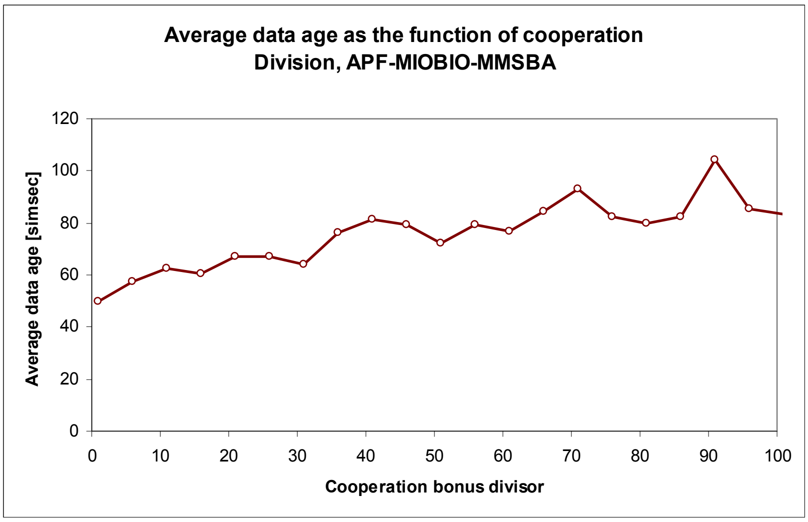

Figure 12 Average data age in function of the cooperation bonus divisor (APF/MIOBIO/MMSBA)

5 Application Possibilities of the New Results

The Location Area planning solutions I have proposed in Thesis 1 produces better performances than the other LA planning algorithms introduced in the literature. Since all the existing cellular networks use the zone-based Location Update scheme in practice, my thesis addresses a very important optimization issue in cellular networks. These planning principles could provide the mobile operators to configure LAs in a way which guarantee that signalling load will be kept under tolerable levels, because in third generation mobile telecommunication systems, signalling requirements due to location updating and paging are expected to be remarkable, mainly because of the huge number of mobile subscribers. Location Area planning is an important issue in the design of high-performance mobile networks, since it could have a serious impact on the total mobility management cost of mobile terminals. To my knowledge the mobile operators are still not optimizing the LA planning, therefore by applying these planning principles in Long Term Evolution systems, a significant signalling load decreasement could be achieved.

The deficiency of zone-based schemes in the literature is that they are not dealing with the optimization of the next level of hierarchy, namely how to group these routers on the next level of hierarchy, and on which level of hierarchy to implement the mobility agent functionalities. In Thesis 2 I introduced a hierarchical network design algorithm, therefore creating a mobility management optimization framework for the entire network segment.

I also investigated how can signalling cost be decreased in different type of networks, like in a disconnected network architecture where highly mobile nodes form the network. I proposed in Thesis 3 novel information dissemination algorithms which will be most likely used in the BIONETS network (BIOlogically inspired NETwork and Services environment) [19] in the future together with the principles of natural selection.

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Publication of the New Results

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