Unified analytical models for location management costs and optimum design of location areas

Eladio Martin, Ling Liu, Matt Weber, Peter Pesti, M. Woodward

Distributed Data Intensive Systems Lab
College of Computing, Georgia Institute of Technology
Atlanta, Georgia, USA
{emartin, lingliu, mattweb, pesti}@cc.gatech.edu

***Abstract*—Within collaborative computing, computer mediated communications are evolving rapidly thanks to the development of new technologies. The facilitation of awareness and discovery of users in the communications networks is a key requirement for the success of these collaborative systems. Besides the need for location awareness, the emergence of heterogeneous wireless environments, where users can freely roam, is making Location Management (LM) an increasingly important topic for network operators. In this paper, we use a general model for LM signaling costs to obtain analytical expressions for their optimization. These expressions are applicable to different LM algorithms and scenarios, contributing towards the development of a standardized performance evaluation technique and to deliver guidelines for the optimum design of Location Areas (LAs). We also illustrate how modifications in the different parameters involved in the LM costs affect the optimum number of cells per LA and the value of the optimum LM costs**.

Keywords: location management, location update, paging, signaling costs.

I. INTRODUCTION

The recent growth in the number of users in mobile communications networks and the rise in the traffic generated by each user, are responsible for the increasing importance of Mobility Management. Within Mobility Management, the main objective of Location Management (LM) is to enable the roaming of the user in the coverage area, and the basic procedures involved are paging and location update (also called location registration in IS-41). Paging consists of searching for the mobile terminal when a call has to be delivered, and is accomplished by means of messages sent to all the candidate cells. Through location update, some predetermined circumstance makes the mobile terminal inform the network about its current location, in order to avoid being paged in all the cells of the network when a call for it arrives. The transmission of all these messages through the air path and the fixed network poses an important signaling burden, especially for the radio interface. The minimization of these signaling costs has become a key research topic.

In existing cellular networks, the coverage area is split into Location Areas (LAs) where the terminals can roam without having to update their locations. The bigger these LAs, the lower the signaling costs involved in location update, but the larger the paging costs. Consequently, the minimization of the LM signaling costs through the optimum design of LAs must take into account the trade-off between the location update and paging costs.

Despite all the research effort that has been recently put into the field of LM, there is still a need for a standardized performance evaluation technique to allow an easy comparison of different LM algorithms and environments. In this paper, we contribute to bridging this gap through the study of the LM costs considering a general format for the location update and paging costs, obtaining analytical expressions to define the optimum point that minimizes the LM costs, and to examine the influence of the variation of the location update and paging costs on the optimum point. These analytical expressions are applicable to different LM algorithms and scenarios, representing an important contribution towards a standardized performance evaluation technique. As will be shown in the next Sections, many of the results that independent researchers find for the specific algorithms and scenarios they propose are perfectly matched with our analytical expressions. In other words, particularizations of our analytical expressions to the conditions and environments proposed by different researchers, deliver results in total agreement with their independently carried out studies. Additional contributions of this paper include: a thorough study of the trade-off between location update and paging costs for urban and highway scenarios, and the inference of practical guidelines for the optimum design of LAs.

Since most of the LM concepts are not protocol dependent [1], the issues considered in this article are applicable to all Personal Communications Services (PCS) networks, and also to next generation wireless networks [2, 3]. Moreover, the basic concepts of LM in Mobile IP are the same as in PCS, with three slight differences [4]: first, in Internet, a subnet cannot be abstracted with a geometric shape; second, distances in Internet are usually counted in terms of the number of hops that the packets travel; and third, instead of paging cost, packet delivery cost should be used to calculate the total LM costs. Furthermore, although a change in backbone network can bring new considerations, many of the concepts used for PCS networks, and some for Mobile IP, will be applicable in some way to the Wireless Asynchronous Transfer Mode (WATM) and Satellite networks [1].

This paper is organized as follows: next Section describes the state of the art in the research about the factors considered for the analysis of the LM costs and about guidelines for the design of LAs. In Section 3, different analytical expressions for the optimum point in LM costs are obtained, studying the trade-off between the components of the costs. In Section 4, our analytical expressions are applied to examine urban and highway scenarios, performing a comparison of the results. Section 5 gathers the conclusions.

II. State Of The Art On The Study Of LM Costs

The requirement for optimum radio resource management will be even more severe in next generation cellular networks, and proper mining of parameters accounting for users' behavior and network infrastructure have recently been suggested for the optimization of LM [5]. Ongoing research on mobile broadband networks such as mobile Wimax coincides on highlighting the need for a LM model considering factors such as the velocity of mobile stations, session arrival rates, paging group size, etc. for the optimization of signaling costs [2]. In the same sense, making use of general probability density functions, reference [6] develops formulae which are subsequently applied to static and dynamic schemes in order to analyze LM and QoS in wireless networks. Other interesting research works focusing on the factors to consider for the analysis of LM costs are summarized next.

Simulation results in [7] show that for all the different versions of the movement-based LM scheme analyzed, the paging costs follow an approximately linear increase with the movement threshold, and the total LM costs follow an approximately convex behavior with it, matching with our results from Section 3. Reference [7] also delves into the trade-off between the location update and paging costs, analyzing how reductions in the former bring increases in the uncertainty of the position of the mobile, translating into rises in the paging costs.

In [8], Fang analyzes the LM costs involved in the movement-based method combined with one-step paging, considering the difference between call inter-arrival times and inter-service times (the former follow exponential distribution considering a Poisson process for the arrival of calls, while the latter should be taken as generally distributed due to the busy line effect). Fang also indicates the analytical approach that could be followed to take into account the service time. Results in [8] show that assuming cell residence time as Gamma distributed and inter-service time as Erlang distributed, the total costs follow a convex function over the movement threshold, and the optimum movement threshold increases with rises in the cost per location update or reductions in the call-to-mobility ratio (CMR). It is also shown that the optimum total costs have low sensitivity to the variances of the cell residence time and the inter-service time, with this sensitivity depending on particular combinations of values of the parameters considered.

Reference [9] examines the performance of the distance-based method combined with selective paging in comparison with the traditional static LA strategy, considering a one-dimensional scenario for simplicity, and random walk as mobility model. To obtain an analytical expression for the LM costs, parameters such as the number of cells per LA, the cost for each location update (C_{LU}), the cost for paging a cell (C_{Pcell}), the call arrival rate (λ_c), the maximum paging delay, and the mean and variance of the cell residence time have been considered. Regarding the variance of the cell residence time, its relevance on the LM costs is only important for low CMRs, when the location update costs account for a significant proportion of the total costs. Results in [9] show that increases in the variance translate into noticeable reductions in absolute terms in the optimal total LM costs.

In the study of the LM costs carried out in [10] for Next Generation Wireless Networks (NGWN) (considered as a collection of subnetworks with the Internet as the common backbone network and where LM is performed by a Subnet Location System for every subnetwork), the following system parameters have been considered: number of subnetworks, size and distribution of cells and LAs within each subnetwork, mobility characteristics and connection request arrival rate.

Reference [11] analyzes the Mobility Management performance of the Cellular IP protocol for mobile packet switched networks. Mobility Management in Cellular IP is based on the two states that the Mobile Host (MH) can adopt: active or idle. In analogy to circuit-switched networks, the LM functions are performed when the MH is in idle state, while Handoff Management functions correspond to the active state. Regardless of the state, while the MH is attached to the network it keeps sending update packets, called Paging Update (PU) packets for the idle state. The LM strategy followed in Cellular IP is a combination between the classical strategy, triggering updates whenever the borders of predetermined sets of cells are crossed, and the timer-based method. To study the performance of this LM strategy, the most important factors considered in [11] are:

- Cost per PU packet sent by the MH when the timer expires (assumed 10/3 for simplicity).
- Cost per PU packet sent by the MH when it moves to a new paging area (assumed 20/3 for simplicity).
- Cost for polling each cell during the MH paging process (assumed 1 for simplicity).
- Cell dwell time for a MH, modeled by an exponential probability density function, with mean $1/\mu_{cell}$.
- CMR, defined as λ_c / μ_{cell} in the study, and assumed as 0.1.
- Timeout period for the PU timer (T_{PUt}), whose influence on the costs will be considered in the call-to-update time ratio (CTR). This parameter CTR= $\lambda_c \cdot T_{PUt}$, follows an inverse proportionality relation with the LM costs.
- Length of long period in which the MH remains in idle state, assumed to be exponentially distributed with mean $1/\lambda_c$, and whose influence on the costs will be considered in the CTR parameter.

Reference [12] studies the LM costs for a strategy based on the movement-threshold method, and which uses the optional Gateway Location Register (GLR) for UMTS. The authors mathematically prove the existence and uniqueness of an optimal movement threshold that minimizes the LM costs for this strategy, and deduce the shape of the total LM costs (C_T) through the following result [12]:

$$\frac{\partial C_T}{\partial d} = \begin{cases} \infty & d \to \infty \\ > 0 & d > d_{\min} \\ = 0 & d = d_{\min} \\ < 0 & 0 < d < d_{\min} \\ -\infty & d \to 0^+, \end{cases} \qquad (1)$$

where d is the movement threshold and d_{min} is its optimal value. In order to properly compare these results with those from our analytical expressions from Section 3, we must notice that the authors of [12] obtain the expression for the paging costs in terms of the total number of cells paged (proportional to d^2) instead of choosing as variable the number of rings of cells paged (linear with d), and consequently the first derivative of the paging cots increases linearly with d. Therefore $\frac{\partial C_T}{\partial d} = \infty$ when $d \to \infty$. Otherwise, this slope would have been a constant, perfectly matching with our results. Also, assuming that declines in the CMR are due to increases in the mobility rate, the authors show a direct relation between d_{min} and the mobility rate, an inverse relation between λ_c and the total costs per call arrival, and an inverse relation between C_{Pcell} and d_{min}. All these results match with our outcome from Section 3.

Reference [13] analyses the optimal design of one-dimensional LAs (highway scenario) by means of continuous formulation in order to avoid computational difficulties inherent in the combinatorial formulation. The analysis considers three optimization methods and different users' density and flow distributions, showing that the optimal LM costs are proportional to $\sqrt{\lambda_c \cdot C_{Pcell} \cdot C_{LU}}$, and the optimal size of LAs are inversely proportional to $\sqrt{\lambda_c \cdot C_{Pcell} / C_{LU}}$, which matches with our results in (8) and (9) from the generic model in the next Section.

The authors in [14] attempt to solve the trade-off between location update and paging costs, obtaining an analytical expression for the location update costs through the application of the "Traveling Salesman" mobility model, and a formula for the paging costs making use of the "Rule Base Paging Scheme", with the intention to develop a performance evaluation technique to compare different algorithms and study the sensitivity of the costs with the call arrival rate. Nevertheless, all these research works show the need for a unified model for the LM costs working at basic parameter level, allowing an easy performance evaluation, and at the same time facilitating the analysis of the sensitivity of the costs with multiple call and mobility parameters.

III. General Model Of LM Costs

A. Analysis of the costs

Considering a Poisson process for the arrival of calls, with rate λ_c (number of calls per user and per time unit). Calling η the location update rate as the average number of LA borders crossings per user and per time unit, C_{LU} the cost involved in each location update operation, and C_P the cost involved in each paging operation, the total LM costs per user and per time unit for a generic algorithm can be approximated by:

$$C_{Tu} = C_P \cdot \lambda_c + C_{LU} \cdot \eta . \qquad (2)$$

Focusing on C_P, it can be expressed in terms of the cost for paging a single cell, C_{Pcell}, and the expected number of cells polled in each paging operation $E[n]$:

$$C_P = C_{Pcell} \cdot E[n] . \qquad (3)$$

The value of $E[n]$ depends on the particular paging strategy followed. Under one-step paging (also called blanket paging), $E[n]$ would equal the total number of cells per LA, x. But the use of more than one paging step, despite the increase in the call delivery delay, can lead to lower numbers of cells paged, therefore reducing the paging costs [9, 15-19].

Some studies [12, 20] analyze the costs within a particular time interval: the call inter-arrival period. In this case, the total LM costs can be expressed as:

$$C_{Tuc} = C_{Pcell} \cdot E[n] + C_{LU} \cdot \frac{\eta}{\lambda_c}, \qquad (4)$$

where the term η / λ_c corresponds to the inverse of the CMR, a parameter widely used in performance studies such as [21], where the behavior of both the costs and the optimum number of cells per LA are analyzed versus the CMR.

To account for the users' mobility, several models have been proposed in the literature; amongst them (see [22] and references therein), the fluid model, the gravity model, the symmetric random walk, or the Markov model. Within this field, existing research [12, 23] has explained the difficulty to obtain the number of cells borders crossings between two LAs borders crossings when a general distribution is considered for the residence time in a LA. For this reason, in order to simplify the analysis of the costs involved in the fractional movement-based scheme, [23] suggests the assumption of exponential distributions for the residence times of the mobile in a cell and in a LA. On the other hand, [24] considers actual data from the operators instead of assumptions to account for the call and mobility models of the users, and approximates the cell crossing rate in idle state by the handoff rate in active state.

In this work, assuming a fluid flow mobility model with a deployment of square cells of side length L, the location update rate per user can be expressed in terms of parameters such as the density of users, ρ, the mean number of outgoing terminals from a LA, $E[out]$, and the number of cells per LA, x [25]:

$$\eta = \frac{E[out]}{\rho \cdot L^2 \cdot x}. \qquad (5)$$

Considering the location update rate per amount of users in a LA, η_{LA}, it can be expressed in terms of the results from [25] as:

$$\eta_{LA} = \frac{4\rho \cdot E[v] \cdot L}{\pi} \cdot \sqrt{x}, \qquad (6)$$

where $E[v]$ represents the mean velocity of the users. And making use of (6), the total LM costs per amount of users in a cell and per time unit, using blanket paging, can be approximated by:

$$C_{Tc} \approx (\lambda_c \cdot \rho \cdot L^2) \cdot C_{Pcell} \cdot x + \frac{C_{LU} \cdot \eta_{LA}}{x} = \\ = (\lambda_c \cdot \rho \cdot L^2) \cdot C_{Pcell} \cdot x + \frac{C_{LU} \cdot 4\rho \cdot E[v] \cdot L}{\pi} \cdot \frac{1}{\sqrt{x}}. \qquad (7)$$

This expression allows an easy study of the influence of the different parameters in the LM costs and their effect on the optimal design of LAs, which will be tackled in subsequent paragraphs. Some of the results from [25] that have helped us to derive (7), are also used in [26] to analyze Mobile IP with an adaptive individual paging technique to minimize signaling. For this purpose, instead of square shapes, hexagonal cells and LAs are assumed, and the signaling burden in the fixed network side is also considered. Results in [26] confirm the dependency of the optimum LA size on $E[v]$, λ_c and the distance of the mobile hosts to their home networks, among other parameters.

In the study of mobile communications networks, the tolerance of the optimum LM costs solution to deviations in the system parameters should be analyzed [27]. Next, considering typical values of the parameters in (7), we will examine the consequences of varying each component of the costs.

B. Study of the trade-off between the components of the costs

For simplicity, in this work C_{Pcell} will be assumed as 1 (units of bytes exchanged), and the C_{LU} / C_{Pcell} ratio will be taken as 17 [28]. Choosing L as 1 km, λ_c as 0.5 call/hour per user, ρ as 200 users/km^2, and $E[v]$ as 4 km/h, (urban scenario) the results in Fig. 1 are obtained.

As can be observed in Fig. 1, 20 is the optimum number of cells per LA that minimizes the total costs (5870 bytes). It can be noticed that the higher the number of cells per LA, the lower the location update costs, as the mobile user is able to roam around a larger surface without updating location. However, this increase in the LA size brings a rise in the number of cells to page, and therefore the paging costs grow. Consequently, the optimum point where the LM costs are minimized, accounts for the trade-off between the location update and the paging costs.

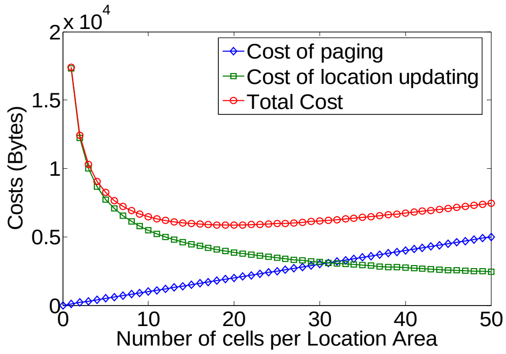


Fig. 1. General behavior of location update, paging and total LM costs in urban scenario.

If the parameters directly proportional to the location update costs are increased, the curve of the referred costs will be lifted, which will translate into a rise in the new optimum LM costs and a slight shift towards the right in the new optimum number of cells per LA. Actually, keeping the paging costs fixed, the described change is mathematically reasoned next:

Referring by x to the parameter that accounts for the size of the area administered by a particular LM algorithm (for simplicity, x can be considered as the number of cells per LA, but depending on the algorithm, it could also represent the threshold distance (usually in terms of rings of cells) from the origin of the user's movement [9, 15, 29], the threshold distance from a VLR working as an agent for the mobile user [30], the threshold number of movements made by the user since the last interaction user-network [7, 8, 16, 20, 23], the maximum length of a forwarding pointer [31], etc.). Taking a generic format for the paging costs: $P = A{\cdot}x$, (for simplicity, A will be assumed independent of x), and a generic format for the location update costs: $L = B{\cdot}(1/x)$, (again for simplicity, B will be assumed independent of x), the total costs can be expressed as: $C_T = P + L = A{\cdot}x + B{\cdot}(1/x)$. To study the positioning of the optimum of the total costs, calculating the derivative with respect to x and equating to zero, the following result is obtained:

$$x_{opt} = \sqrt{\frac{B}{A}} = \sqrt{\frac{C_{LU}\cdot\eta_{LA}}{\lambda_c\cdot\rho\cdot L^2\cdot C_{Pcell}}}\,. \tag{8}$$

$$C_T\big|_{x=x\ opt} = 2\sqrt{B\cdot A} = 2\sqrt{C_{LU}\cdot\eta_{LA}\cdot\lambda_c\cdot\rho\cdot L^2\cdot C_{Pcell}}\,. \tag{9}$$

Consequently, keeping the paging costs fixed, any rise in the location update costs will bring an increase in the value of x_{opt}, i.e., an enlargement in the optimum number of cells per LA, and a growth in the corresponding LM costs, $C_T\big|_{x=x\ opt}$, as we wanted to prove.

Making use of the previous reasoning, it can be concluded that keeping the location update costs fixed, any increase in the paging costs ($A_2>A_1$) will bring a decline in the optimum number of cells per LA: $\sqrt{\frac{B}{A_2}} < \sqrt{\frac{B}{A_1}}$, and a rise in the optimum costs : $2\sqrt{A_2\cdot B} > 2\sqrt{A_1\cdot B}$.

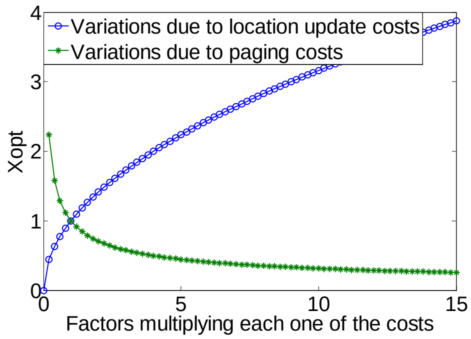
The previous proof can be extrapolated to a more complex format of the costs, which is the one that we will use subsequently to obtain results, where the variability of the location update costs with the number of cells per LA, x, is expressed according to the final format of (7) in terms of $\frac{1}{\sqrt{x}}$, instead of $\frac{1}{x}$. Although the results obtained considering this second model differ from the first one, the guidelines for the behavior of the optimum point remain the same. Specifically, following the same steps as in the previous proof, the results obtained are:

$$\frac{\partial C_T}{\partial x} = 0 \Rightarrow x_{opt} = \left(\frac{B}{2\cdot A}\right)^{\frac{2}{3}} = \left(\frac{C_{LU}\cdot 2\cdot E[v]}{\lambda_c\cdot C_{Pcell}\cdot L\cdot\pi}\right)^{\frac{2}{3}}. \tag{10}$$

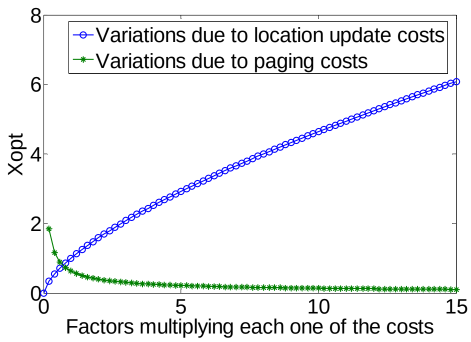
$$\begin{aligned} C_T\big|_{x=x\ opt} &= A\cdot\left(\frac{B}{2A}\right)^{\frac{2}{3}} + B\cdot\frac{1}{\sqrt{\left(\frac{B}{2A}\right)^{\frac{2}{3}}}} = \\ &= \left[\left(\frac{1}{2}\right)^{\frac{2}{3}} + 2^{\frac{1}{3}}\right]\cdot\left[A\cdot(B)^2\right]^{\frac{1}{3}} = \\ &= \left[\left(\frac{1}{2}\right)^{\frac{2}{3}} + 2^{\frac{1}{3}}\right]\cdot\rho\cdot\left[\frac{16\cdot\lambda_c\cdot C_{Pcell}\cdot L^4\cdot C_{LU}{}^2\cdot(E[v])^2}{\pi^2}\right]^{\frac{1}{3}}. \end{aligned} \tag{11}$$

The main difference of this second model in comparison with the first one, is the fact that the variations in the total costs will follow distinct scales depending on whether the paging costs or the location update costs are changed (1/3 power growth when the former costs rise and 2/3 power growth when the latter costs increase). On the other hand, the swings in the total costs were the same in the first model, regardless of which particular cost was modified. Graphically, the variations in the optimum number of cells per LA for both models are shown in Fig. 2.

As observed in Fig. 2, the curvature of the decline of the optimum number of cells per LA with the paging costs is more emphasized in the second model, and the rise with the increase in the location update costs is less important in the first model. It can be noticed that when the location update costs are very low, slight increases in their value bring quick enlargements in the optimum number of cells per LA. On the other hand, once the location update costs go above a threshold, much higher rises in their value are required for enlargements of the same size in the optimum point. This same behavior can be noticed for the paging costs, changing enlargements by reductions in the optimum number of cells per LA.



a) Generic model



b) More complex model

Fig. 2. Evolution of the optimum point that minimizes LM costs, with variations in location update and paging costs.

Considering particular values for each one of the parameters in (7), for example L ranging between 0.15 and 5 km, varying λ_c from 0.01 to 10 call/hour per user, ρ between 1 and 10000 users/km^2, and $E[v]$ from 3 to 70 km/h, the constants for the location update and paging costs vary within the intervals $[0.57,\ 4.46 \cdot 10^6]$ and $[2.25 \cdot 10^{-4},\ 2.5 \cdot 10^6]$ respectively. As a result, cases with very high numbers of cells per LA tend to occur for short lengths of the cell side (below 1 km), together with low call arrival rates (below 0.1 call/hour per user) and moderate or high mean users velocity (above 10 km/h). However, it must be noticed that according to (10) there is no direct relation of ρ with the optimum number of cells per LA (there will be an indirect relation through L, as growths in ρ tend to bring reductions in L).

IV. Study Of Particular Scenarios

In this Section, two particular scenarios, urban and highway, will be studied. We consider that these two scenarios account for some of the most common conditions to deal with in LM. Moreover, this election is backed by existing works that uphold this line of study. For instance, in the LM performance analysis carried out in [10] for NGWN, instead of checking the effect of the variation of every parameter in the costs, two representative scenarios are analyzed, focusing on the outcome of modifying the call and mobility rates. Reference [32] justifies the importance of the analysis of an urban scenario, due to the high users' density and mobilities involved, making of it one of the worst case environments for future mobile communications networks. And the performance analysis of the scheme proposed in [33] classifies the considered population into slow and fast moving users, and assigns them urban and highway scenarios respectively to carry out the study.

A. Urban scenario

Recalling the urban scenario described in Section 3 with an optimum number of 20 cells per LA and with 5870 bytes per cell and per hour for the LM costs, if the location update costs are reduced by half, the changes produced in the optimum point can be observed in Fig. 3.

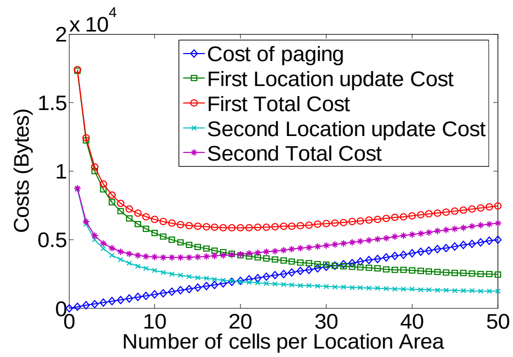


Fig. 3. Variability of the optimum point for urban scenario, when location update costs are reduced by half.

From the study of different cases of variations in the location update costs, it can be concluded that increases in the location update costs bring rises in the total costs for the optimum point, and growths in the range of numbers of cells per LA where the value of the total costs is approximately the same as for the optimum point (because the new minimum is not so sharp in shape). On the other hand, when the location update costs are reduced, the new total costs fall, and the new minimum is much sharper in shape, consequently reducing the range of points around the minimum presenting values for the costs similar to the optimum, therefore restricting the freedom of the designer at the time of choosing a particular deployment. Calling F the factor multiplying the location update costs, and R the range of numbers of cells per LA where the total costs are similar to the optimum point, numerical results are summarized in Table I.

TABLE I. Variation of the optimum point of LM costs with changes in the location update costs in urban scenario.

F	New x_{opt}	New C_T	R
0.1	4	1266	[3,4]
0.5	12	3698	[10,14]
2	31	$9.31 \cdot 10^3$	[25,36]
4	49	$1.47 \cdot 10^4$	[35,60]
6	64	$1.94 \cdot 10^4$	[45,80]
8	78	$2.35 \cdot 10^4$	[60,100]
10	91	$2.72 \cdot 10^4$	[65,115]

Varying the parameters affecting the paging costs, an example for the changes in the optimum point can be observed in Fig. 4.

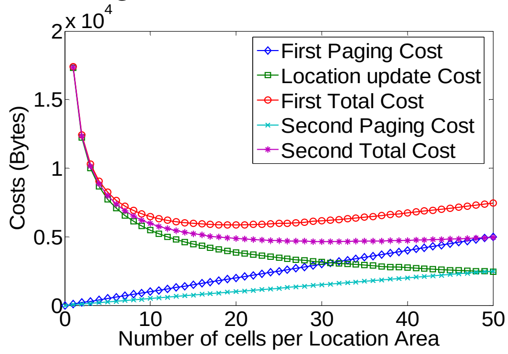


Fig. 4. Variability of the optimum point for urban scenario, when paging costs are reduced by half.

Growths in the paging costs make the optimum point much better distinguished, therefore restricting the designer's freedom. On the contrary, declines in the paging costs, make the range of possible numbers of cells per LA for the optimum point much wider. Results are summarized in Table II.

TABLE II. VARIATION OF THE OPTIMUM POINT OF LM COSTS WITH CHANGES IN THE PAGING COSTS IN URBAN SCENARIO.

F	New x_{opt}	New C_T	R
0.1	91	2724	[70,120]
0.5	31	4660	[26,45]
2	12	7396	[11,14]
4	8	9320	[6,10]
6	6	$1.066 \cdot 10^4$	[5,7]
8	5	$1.175 \cdot 10^4$	[4,6]
10	4	$1.266 \cdot 10^4$	[4,5]

B. Highway scenario

Assuming as parameters for an example of highway scenario the following: λ_c = 1 call/hour per user, L = 5 km, $E[v]$ = 70km/h and ρ = 100 users/km^2, we obtain 28 as the optimum number of cells per LA, with the total LM costs per cell and per hour: $2.13 \cdot 10^5$ bytes. Following the same steps as in the study of the urban scenario, the changes in the optimum point for the LM costs in a highway scenario can be summarized with Figs. 5 & 6 and Tables III & IV.

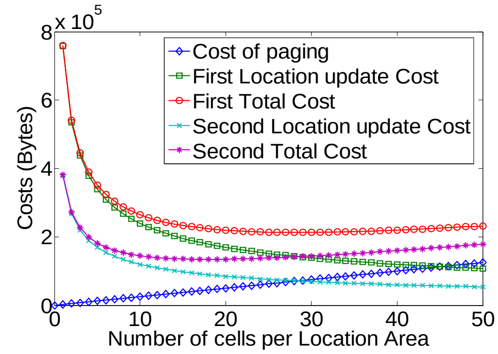


Fig. 5. Variability of the optimum point for highway scenario, when location update costs are reduced by half.

For this scenario, the optimum point is not so well distinguished with reductions in the location update costs in comparison with the urban scenario. Actually, the range in the number of cells per LA bringing a quantity of total costs similar to the optimum point is wider than in the urban scenario for the cases analyzed. However, it must be noticed that for increases in the location update costs, the referred range is very wide for both scenarios.

TABLE III. VARIATION OF THE OPTIMUM POINT OF LM COSTS WITH CHANGES IN THE LOCATION UPDATE COSTS IN HIGHWAY SCENARIO.

F	New x_{opt}	New C_T	R
0.1	6	$4.6 \cdot 10^4$	[5,8]
0.5	18	$1.343 \cdot 10^5$	[13,20]
2	45	$3.384 \cdot 10^5$	[33,65]
4	72	$5.37 \cdot 10^5$	[57,88]
6	94	$7.04 \cdot 10^5$	[70,120]
8	114	$8.53 \cdot 10^5$	[85,140]
10	132	$9.894 \cdot 10^5$	[95,160]

Fig. 6 illustrates an example of changes in the optimum point due to the variations in the paging costs.

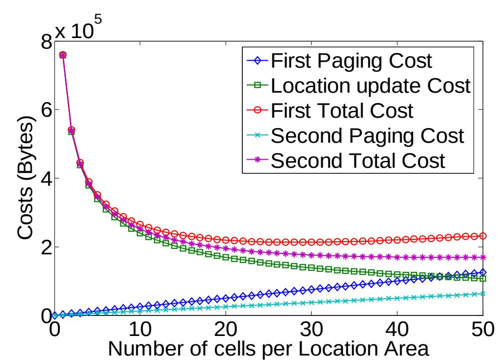


Fig. 6. Variability of the optimum point for highway scenario, when paging costs are reduced by half.

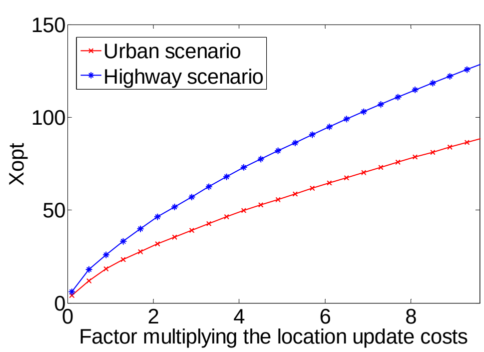
Again, rises in the paging costs, apart from diminishing the number of cells per LA of the optimum point, give a better distinguished optimum point. On the other hand, reductions in the paging costs enlarge the range of possible numbers of cells per LA that produce an amount of total costs similar to that of the optimum point. Results are summarized in Table IV.

TABLE IV. VARIATION OF THE OPTIMUM POINT OF LM COSTS WITH CHANGES IN THE PAGING COSTS IN HIGHWAY SCENARIO.

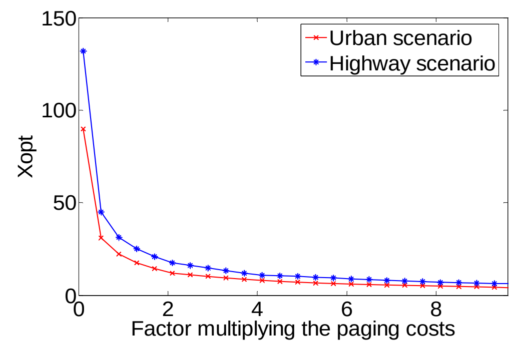
F	New x_{opt}	New C_T	R
0.1	132	$9.89 \cdot 10^4$	[115,160]
0.5	45	$1.69 \cdot 10^5$	[34,60]
2	18	$2.685 \cdot 10^5$	[16,21]
4	11	$3.385 \cdot 10^5$	[9,13]
6	9	$3.875 \cdot 10^5$	[7,10]
8	7	$4.265 \cdot 10^5$	[6,8]
10	6	$4.595 \cdot 10^5$	[5,7]

C. Comparison of results between urban and highway scenarios.

Two different cases can be observed in both scenarios regarding the variation in the optimum number of cells per LA: the first one (Fig. 7.a), in which only the location update costs are changed, is characterized by a square root type behavior of the optimum numbers of cells with the increase of the location update costs and presents a wider range of variation in absolute terms in the highway scenario than in the urban scenario (a fluctuation from 6 to 132 in comparison with the [4, 91] interval). The second case, (Fig. 7.b), in which only the paging costs are changed, is characterized by an exponential decline in the optimum number of cells with increases in the paging costs. This, again, presents a wider range in absolute terms in the highway scenario than in the urban one. However, in relative terms, the fluctuations are the same for both scenarios for each case separately: 79% reduction for both scenarios in the optimum number of cells for a 10 times increase in the paging costs, and 360% rise for both scenarios in the optimum number of cells for a 10 times growth in the location update costs. Considering at the same time increases and reductions by 10 times for each particular cost, the overall percentage variation is the same for both cases: 2150%.



a) Location Update Costs are varied.

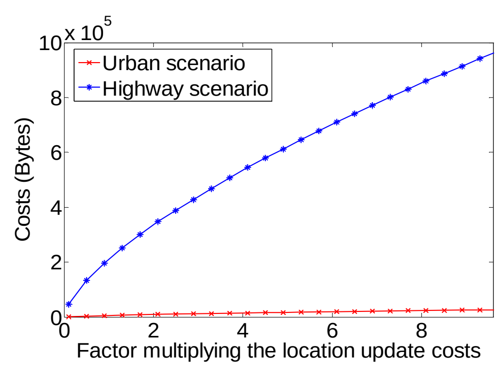


b) Paging Costs are varied.

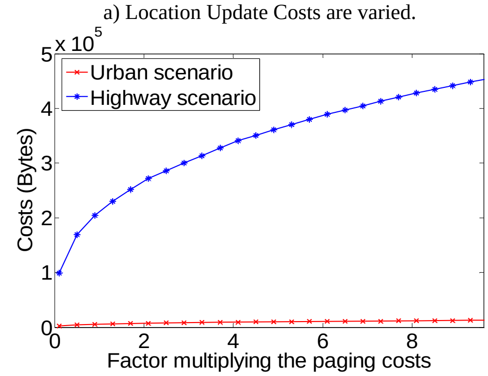
Fig. 7. Comparison between the urban and highway scenarios in the optimum number of cells per LA when the components of the LM costs are varied.

Regarding the variations in the total costs for the optimum point, they present square root type behavior for both scenarios, regardless of the location update or paging costs being increased, as can be observed in Fig. 8.

Although in absolute terms, the rise in the total costs for the optimum point due to increases in either of the costs, is more important in the highway scenario, in relative terms, the rises for both scenarios are the same in each case separately. Nevertheless, the alterations in the total costs due to swings in the location update costs are larger than those due to variations in the paging costs.



a) Location Update Costs are varied.



b) Paging Costs are varied.

Fig. 8. Comparison between the urban and highway scenarios in the optimum total costs when the components of the LM costs are varied.

V. CONCLUSIONS

The behavior of the optimum point where the LM costs are minimized has been studied in this article, by means of the mathematical analysis of the trade-off between the location update and paging costs.

If the parameters involved in the location update costs are increased while the paging costs are kept constant, the new optimum total costs will be higher (2/3 power growth considering the second model from Section 3), and the new optimum number of cells per LA will go up (again 2/3 power rise considering the second model). If the paging costs are increased while the location update costs remain fixed, the optimum number of cells per LA will drop (-2/3 power evolution considering the second model), and the optimum total costs will pick up (1/3 power growth for the second model).

When both location update and paging costs are very low, any slight modification in the paging costs brings much more important variations in the optimum number of cells per LA than any swing of the same size in the location update costs. On the other hand, once both costs exceed a threshold, any variation in the paging costs will produce negligible changes in the value of the optimum point in comparison with the modifications brought by the same large alterations in the location update costs.

Examining the behavior of the optimum point for urban and highway scenarios, we draw the following conclusions:

- Reductions in the location update costs and rises in the paging costs make the optimum point for the LM costs become more distinguished, therefore restricting the freedom of the designer to choose between possible deployments with similar costs.

- In absolute terms, the range of variation in the optimum number of cells is wider in the highway scenario than in the urban one regardless of the location update or the paging costs being modified, although in relative terms, the variation ranges are the same for both scenarios for each type of cost separately.

- When both types of costs are increased by the same factor, the variations in the optimum number of cells brought by rises in the location update costs are larger than those produced by growths in the paging costs. On the other hand, when both costs are diminished by the same factor, the variations in the optimum number of cells produced by reductions in the paging costs are more important than those brought by declines in the location update costs.

- In absolute terms, the rise in the total costs for the optimum point when any of the costs picks up is much more important in the highway scenario, although in relative terms, the growths are the same for both scenarios for each type of cost separately. However, the modifications in the total costs due to increases in the location update costs are larger than those due to rises of the same size in the paging costs.

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