An Hybrid Movement–Distance–Based Location Update Strategy for Mobility Tracking[1]

Vicente Casares-Giner, Pablo García-Escalle

Universidad Politécnica de Valencia
Departamento de Comunicaciones
Camino de Vera s/n, 46022 Valencia -Spain
e-mail: {vcasares,pgarciae}@upvnet.upv.es

***Abstract*: In this paper we propose a location update (LU) scheme which is mobile terminal (MT) dependent. Each mobile terminal stores a set of cells within a distance H, in terms of cells, from the cell where the last update occurred. The mobile can then move freely within this set of cells without the need for update. When the MT makes a number of d movements outside of the memorized set of cells, a location update is triggered and a new set of cells is memorized. Each time the MT visits one of the memorized cells its movement counter is reset. This hybrid scheme is indeed an intermediate solution between the wellknown movement–based and distance–based schemes. Selective paging is also considered since it provides a significant reduction of the paging cost under a small increase in the allowable paging delay. The proposed LU scheme has been analyzed by using Markovian standard models. The results obtained from our analytical model show that, with little memory requirements in the MT very good performances can be obtained, close to the distance–based scheme.**

1. Introduction

Mobility tracking is the set of procedures by which a wireless Personal Communications Services (PCS) network keeps track of the location of *Mobile Terminals* (MTs) at any time. In GSM terminology, these procedures can be classified in two functional areas called *Location Update* (LU) and *Call Delivery* (CD). The *Call Delivery* procedures can be further decomposed into *Interrogation* (IG) and *Terminal Paging* (PG).

In the static or global LU procedures, the whole coverage area is divided into several fixed *Location Areas* (LAs)[2]. An LA is composed by several neighboring cells. Each time an MT crosses the border between two LAs, an LU message is sent to the *Fixed Network* (FN) notifying that a new LA is being visited. The *System Data Base* (SDB) stores the area from which the last LU was reported. On the other hand, the dynamic or local LU strategies are MT dependent. Bar-Noy, Kessler and Sidi propose in [3]-[4] three of these algorithms. Under these three schemes, LU messages are triggered based on the time elapsed, T (the time threshold), the number of movements performed, d (the movement threshold), and the distance traveled, D (the distance threshold), respectively, since the last LU.

In the interrogation procedure, entirely implemented in the FN, when an incoming call arrives, the PCS network must first search in the SDB to find out the area visited by the MT. The output of a successful interrogation is the area where the MT had its last contact. It is followed by the terminal PG procedure in order to find out the exact cell where the MT is actually in.

In this paper we combine two dynamic or local LU strategies, the movement–based and the distance–based. In our proposal, the MT stores the identification of a number of M cells. This set could be, an empty set, the whole set of cells within a distance $D-1$ from the cell where the last LU occurred, or some intermediate option between the two previous. Also, the MT has a movement-counter. Each time the MT visits a cell whose identification is memorized, the movement-counter is reset, i.e. set to zero. Otherwise, the movement-counter is incremented in one unit. When the movement-counter reaches a predetermined value d, the MT triggers an LU message, resets its counter and updates the set of M records. Selective or multi-step paging, [7], is also combined with the LU algorithm. When an incoming call arrives, the FN pages the cells within a distance $D-1$, in terms of cells, from the cell where the last update occurred. A selective paging scheme based on a shortest-distance-first (SDF) partition scheme is used. Cost functions are defined for LU and for selective PG.

2. Scenario and system description

The coverage area of a PCS network is partitioned into cells of the same size. The residence time of an MT in a cell is distributed according to a random variable with probability density function (*pdf*), denoted by $f_m(t)$ which Laplace transform is $f_m^*(s) = \int_0^\infty f_m(t)e^{-st}dt$, and mean value $\frac{1}{\lambda_m}$. When the MT leaves a cell, the probability to visit a new cell is proportional to the common perimeter with this new cell (see for instance the routing probabilities in figure 1). Both, mesh and hexagonal cell regular configuration can be considered. However, here we only report numerical results for the hexagonal scenario, due to the fact that, as in [9] is concluded, the same conclusions are derived from both scenarios.

The number of records in the memory of the MT, M, is a non empty set of cells, composed by a set of $H+1$ consecutive rings of cells, from the *center cell* (cell ring 0) up to cell ring H, figure 2. Therefore $M = 3H^2 + 3H + 1$. The relationship between H, d and D, is $D = H + d$. See the hexagonal cell layout, figure 2 a), where configuration $(H, d) = (2, 3)$ is depicted.

Following terminology of [2], in addition to mosaic graph T as figure 2 shows, mosaic graphs M can also be considered. Mosaic graphs are constructed by arranging

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[2]The terms *Registration Area* and *Location Registration* are used on the IS-41 standard, instead of *Location Area* and *Location Updating*

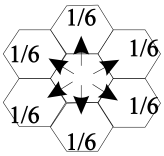


Figure 1. Random walk mobility model (routing probabilities)

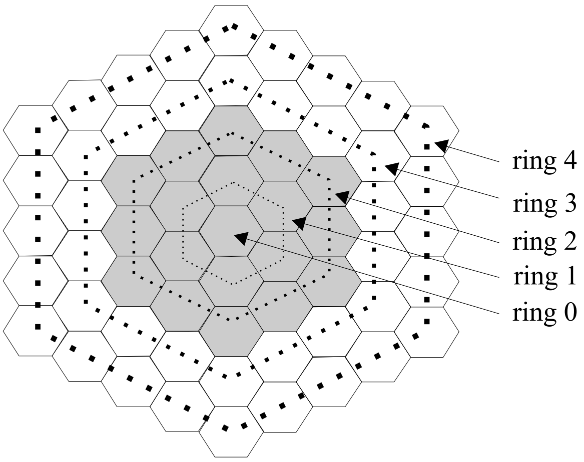


Figure 2. Hexagonal configuration for (H,d)=(2,3) (Dark grey cells configure a mosaic T_2)

cells in concentric cycles around a starting point or a cell. When the center is a point or vertex, figure 3-a, we get the so called mosaic graphs M_m where m denotes the ring number or number of cycles around the center. For mosaic graph M we clearly have $M = 3H^2 + 6H + 3$. When, instead of a point, the center is a cell, figure 3-b, we get dual mosaic graphs, T_m. For T_m, $m = 0$ corresponds to a single hexagon and $m = 1$ corresponds to a cluster of 7 cells.

3. Analytical formulation

We assume that the cell residence time follows the Gamma distribution, with variance V_r. This option is enforced by results of Zonoozi and Dassanayake in [12], where it is shown that the cell residence time can be described by the Gamma distribution. Its Laplace transform is given by

$$f_m^*(s) = \left(\frac{\lambda_m \gamma}{s + \lambda_m \gamma}\right)^{\gamma}; \gamma = \frac{1}{V_r \lambda_m^2} \qquad (1)$$

For incoming calls to the MT it is assumed Poisson arrival process with parameter λ_c. In [15] a general inter-arrival time distribution was assumed for the analysis of [9] but no substantial qualitative differences has

	$f_{0,0}^{(1)}$	$f_{0,1}^{(1)}$	$f_{m,m-1}^{(1)}$	$f_{m,m}^{(1)}$	$f_{m,m+1}^{(1)}$
Mosaic T	0	1	$\frac{2m-1}{6m}$	$\frac{2m}{6m}$	$\frac{2m+1}{6m}$
Mosaic M	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{2m}{6m+3}$	$\frac{2m+1}{6m+3}$	$\frac{2m+2}{6m+3}$

Table 1. $f_{i,j}^{(1)}$ for different hexagonal cell layout configurations

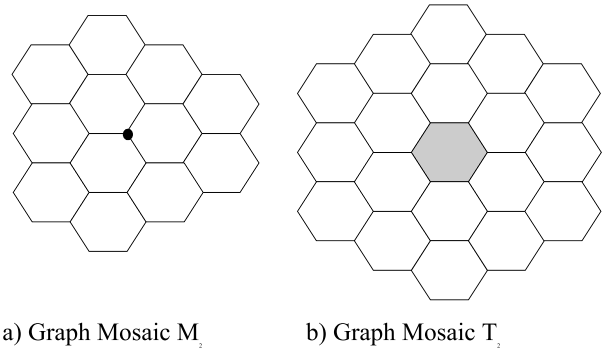


Figure 3. Mosaic graphs, a) M_2 and b) T_2

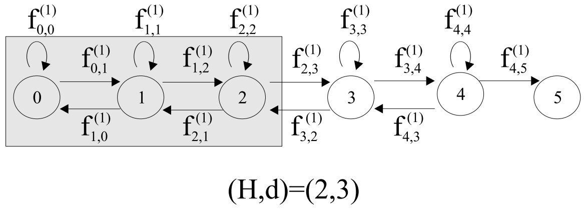


Figure 4. State transition diagram for the cell layout configuration with random walk mobility of figure 2

been found. Therefore, for the sake of easy mathematical reading, our analysis is carried out under the assumption of a Poisson process. Also it is assumed that the call duration is negligible compared with the inter-arrival time duration, such that the busy line effect does not occur [10] (i.e., there is no new phone call to an MT when it is in conversation). Therefore, the probability that there are z boundary crossings between two call arrivals, $\alpha(z)$, derived by Lin in [11], is given by:

$$\alpha(z) = \begin{cases} 1 - \frac{1}{\theta}(1-a); & z = 0 \\ \frac{1}{\theta}(1-a)^2 a^{z-1}; & z > 0 \end{cases} \qquad (2)$$

where $a = f_m^*(\lambda_c)$, and $\theta = \lambda_c/\lambda_m$ is the call-to-mobility ratio, CMR, defined in [5].

3.1. Location update cost

For a given number of movements, z, we are interested in the number of LU messages triggered by the MT. Figure 4 represents the Markov chain for the cell layout configuration of figure 2, mesh or hexagonal random walk. We say that the MT is in state S_i if it is roaming in a cell ring i. According to [1], we call $f_{i,j}^{(n)}$ the conditional probability that state S_j is avoided at times $1, 2, .., n-1$ and entered at time n, given that state S_i is occupied initially. Similarly $_k f_{i,j}^{(n)}$ is the taboo probability that the Markov chain enters state S_j for the first time at the n^{th} step, having initially started from state S_i and avoiding state S_k. Obviously $_k f_{i,j}^{(1)} = f_{i,j}^{(1)}$. Starting from a state S_0, the MT counter is set to zero. The counter is not increased while the Markov chain makes transitions between the set of states S_0, S_1, .., S_H. The MT counter is set to one when the transition $S_H \rightarrow S_{H+1}$ occurs. Therefore, after the transition $S_H \rightarrow S_{H+1}$, if an absorption into state S_H occurs before $d-1$ consecutive movements, the MT resets its movement counter; and when the counter reaches the movement threshold d without being absorbed into state S_H, the MT triggers an LU. Let $P_{nab}(H,d)$ denote the probability that after visiting state S_H the MT triggers an LU within the next consecutive d movements (*nab* = no absorption). $P_{nab}(H,d)$ is given by

$$P_{nab}(H,d) = 1 - f^{(1)}_{H,H-1} - \sum_{n=1}^{d} {}_{H-1}f^{(n)}_{H,H} \quad (3)$$

Let $P_{m,k}(z,d)$ denote the probability of having k LU messages triggered in z movements, given that state S_m is occupied initially. We can write the following recursive relationships. We assume that $H > 0$. The analysis for $H = 0$ was presented in [14], although it can be easily derived from our present study as a particular case.

For $m = 0$

$$P_{0,k}(z,d) = \begin{cases} 1; & k=0, \quad z<D. \\ \sum_{l=0}^{1} f^{(1)}_{0,l} P_{l,0}(z-1,d); & k=0, \quad z \geq D. \\ 0; & k>0, \quad z<kD. \\ \sum_{l=0}^{1} f^{(1)}_{0,l} P_{l,k}(z-1,d); & k>0, \quad z\geq kD. \end{cases} \quad (4)$$

For $m = 1, 2, .., H-1$

$$P_{m,k}(z,d) = \begin{cases} 1; & k=0, \quad z<D-m. \\ \sum_{l=m-1}^{m+1} f^{(1)}_{m,l} P_{l,0}(z-1,d); & k=0, \quad z \geq D-m. \\ 0; & k>0, \quad z<kD-m. \\ \sum_{l=m-1}^{m+1} f^{(1)}_{m,l} P_{l,k}(z-1,d); & k>0, \quad z\geq kD-m. \end{cases} \quad (5)$$

and for $m = H$

$$P_{H,k}(z,d) = \begin{cases} 1; \quad k=0, \quad z<d. \\ \sum_{n=1}^{d} {}_{H-1}f^{(n)}_{H,H} P_{H,0}(z-n,d) + \\ \quad f^{(1)}_{H,H-1} P_{H-1,0}(z-1,d); \quad k=0, \quad z\geq d. \\ 0; \quad k>0, \quad z<kD-H. \\ \sum_{n=1}^{d} {}_{H-1}f^{(n)}_{H,H} P_{H,k}(z-n,d) + \\ \quad f^{(1)}_{H,H-1} P_{H-1,k}(z-1,d) + \\ \quad P_{nab}(H,d) P_{0,k-1}(z-d,d); \\ \quad k>0, \quad z\geq kD-H. \end{cases} \quad (6)$$

Let $M_m(z,d) = \sum_k kP_{m,k}(z,d)$ be the expected number of location update messages triggered by the MT in z movements, given that state S_m is occupied initially. For a Poisson call arrival process with rate λ_c, and using the recursive equations that have been found for $M_m(z,d)$ in a parallel way to (4)-(6), see [13], the location update cost can be written as,

$$C_u(H,d) = U \sum_{z=D}^{\infty} \alpha(z) M_0(z,d) = U \frac{(1-a)^2}{a\theta} M_0^*(a,d) \quad (7)$$

where $M_0^*(a,d)$, expression (8), is given at the top of the next page. The cost of each LU, denoted by U is independent of the location of the MT. U includes the cost of transferring from the FN to the MT the set of M new records corresponding to the identifications of the cell ring $H+1$.

In (8), $M^*_m(a,d) = \sum_{z=D-m}^{\infty} a^z M_m(z,d)$, for $m = 0, 1, ..H$. It is proved in [13] that $M^*_m(a,d) = R^*_m(a) M^*_0(a,d)$ for $m = 0, 1, ..H$. Furthermore $R^*_H(a)$ and $R^*_{H-1}(a)$ can be evaluated with the following forward recursion, (see [13] for further details)

$$R^*_m(a) = \begin{cases} 1; & m=0. \\ \dfrac{1-af^{(1)}_{0,0}}{af^{(1)}_{0,1}}; & m=1. \\ \dfrac{1-af^{(1)}_{m-1,m-1}}{af^{(1)}_{m-1,m}} R^*_{m-1}(a) - \\ \quad \dfrac{f^{(1)}_{m-1,m-2}}{f^{(1)}_{m-1,m}} R^*_{m-2}(a); & m\geq 2. \end{cases} \quad (9)$$

Let $p^{(n)}_{i,j}$ denote the conditional probability that starting in state S_i we enter state S_j at time n (not necessarily for the first time). With $p^{(0)}_{0,0} = 1$; $p^{(n)}_{i,j}$, $f^{(n)}_{i,j}$ and $p^{(n)}_{j,j}$ are related by the convolution equation

$$p^{(n)}_{i,j} = \sum_{k=1}^{n} f^{(k)}_{i,j} p^{(n-k)}_{j,j} \quad (10)$$

Therefore, when computing ${}_{H-1}f^{(n)}_{H,H}$ we bear in mind that, for our Markov chain, we have

$${}_{H-1}f^{(n)}_{H,H} = \begin{cases} p^{(1)}_{H,H}; & n=1. \\ f^{(1)}_{H,H+1} f^{(n-1)}_{H+1,H}; & n>1. \end{cases} \quad (11)$$

Obviously $f^{(1)}_{i,j} = p^{(1)}_{i,j}$. Hence, using (10) $f^{(n)}_{H+1,H}$ can be computed from $p^{(n)}_{H+1,H}$, and from previous values of $f^{(k)}_{H+1,H}$ and $p^{(k)}_{H,H}$, $k = 1, .., n-1$.

3.2. Terminal paging cost

For paging procedure, we use a *shortest-distance-first* (SDF) partitioning scheme, [9]. Let $\pi_{m,i}(z,d)$ $i \in [0, D-1]$ denote the probability that starting at cell ring m the MT is located in cell ring i after z movements. Then, we can write the following recursive relationship

For $m = 0$

$$\pi_{0,i}(z,d) = \begin{cases} p^{(z)}_{0,i}; & z<D. \\ \sum_{l=0}^{1} f^{(1)}_{0,l} \pi_{l,i}(z-1,d); & z\geq D. \end{cases} \quad (12)$$

$$M_0^*(a,d)=\sum_{z=D}^{\infty}a^zM_0(z,d)=\frac{1}{(1-a)}\frac{a^dP_{nab}(H,d)}{R_H^*(a)[1-\sum_{n=1}^{d}a^n\ {}_{H-1}f_{H,H}^{(n)}]-af_{H,H-1}^{(1)}R_{H-1}^*(a)-a^dP_{nab}(H,d)} \quad (8)$$

For $m=1,2,..,H-1$

$$\pi_{m,i}(z,d)=\begin{cases}p_{m,i}^{(z)}; & z<D-m.\\ \sum_{l=m-1}^{m+1}f_{m,l}^{(1)}\pi_{l,i}(z-1,d); & z\geq D-m.\end{cases} \quad (13)$$

and for $m=H$

$$\pi_{H,i}(z,d)=\begin{cases}p_{H,i}^{(z)}; & z<d.\\ \sum_{n=1}^{d}\ {}_{H-1}f_{H,H}^{(n)}\pi_{H,i}(z-n,d)+ & \\ \quad f_{H,H-1}^{(1)}\pi_{H-1,i}(z-1,d)+ & \\ \quad P_{nab}(H,d)\pi_{0,i}(z-d,d); & z\geq d.\end{cases} \quad (14)$$

After performing some algebra, we can get the probability that the MT is in cell ring i when a call arrival occurs, $q_{0,i}(a,d)$. It is given by equation (15) at the top of the next page.

In (15) $q_{m,i}(a,d)=\sum_{z=0}^{\infty}\alpha(z)\pi_{m,i}(z,d)$, for $m=0,1,..H$. It is proved in [13] that $q_{m,i}(a,d)=R_m^*(a)q_{0,i}(a,d)+G_{m,i}^*(a)$, for $m=0,1,..H$. Furthermore $G_{H,i}^*(a)$ and $G_{H-1,i}^*(a)$ can be evaluated with the following forward recursion, (see [13] for further details)

$$G_{m,i}^*(a)=\begin{cases}0; & m=0.\\ -\frac{b_{0,i}}{af_{0,1}^{(1)}}; & m=1.\\ \frac{1-af_{m-1,m-1}^{(1)}}{af_{m-1,m}^{(1)}}G_{m-1,i}^*(a)- & \\ \quad\frac{f_{m-1,m-2}^{(1)}}{f_{m-1,m}^{(1)}}G_{m-2,i}^*(a)- & \\ \quad\frac{b_{m-1,i}}{af_{m-1,m}^{(1)}}; & m\geq 2.\end{cases} \quad (16)$$

with

$$b_{m,i}=\alpha(0)p_{m,i}^{(0)}+[\alpha(1)-a\alpha(0)]p_{m,i}^{(1)}; m=0,1,..H. \quad (17)$$

It can be seen that, when $(H,d)=(0,D)$ equation (15) simplifies to equation (8) of [14].

Therefore, using (15) we compute expressions (11), (12), (13) and (14) of [9]. So the expected terminal paging cost per call arrival, denoted by C_v, is

$$C_v(H,d)=V\sum_{k=0}^{l-1}[\sum_{r_i\in A_k}q_{0,i}(a,d)\sum_{m=0}^{k}\sum_{r_j\in A_m}g(j)] \quad (18)$$

In (18), V is the cost for polling a cell, $l=\min(\eta,D)$, η is the maximum allowable paging delay, $g(i)$ is given by expression (1) of [9], and subarea A_j contains rings s_j to e_j where s_j and e_j are the indices of the first and the last rings in subarea A_j. e_j and s_j are also given in [9].

4. Performance evaluation and numerical results

The total cost per call arrival is defined as

$$C_T(H,d)=C_u(H,d)+C_v(H,d) \quad (19)$$

$C_T(H,d)$, in short notation C_T, can be evaluated for different scenarios under the influence of several parameters. For both mosaic graphs, T and M, table 1 shows the set of probabilities $f_{i,j}^{(1)}$.

The study of the effect of cell residence time variance on performance, has been carried out with some details in [9] for the movement-based strategy. Similar conclusions can be derived in our general framework, so this analysis is omitted in our paper. Therefore, here we opt for exponential residence time for MT, $\gamma=1$. Also, we set $U=10$, $V=1$, as in [9].

All plots represent C_T for mosaic T. For instance, figure 5 shows the total cost C_T, for $CMR=0.01$ and $\eta=1$ (blanket polling). C_T varies widely as D changes. For a given D, in the same column, we plot a set of $D+1$ values. The first value corresponds to the movement-based strategy, (no memory requirements in the MT). The second value corresponds to $(H,d)=(0,D)$. The third value corresponds to $(H,d)=(1,D-1)$,.. and so on. The last value is for $(H,d)=(D-1,1)$ and coincides with the distance-based strategy. Clearly, the value of C_T for distance strategy is lower than the value of C_T for movement strategy. This conclusion is in agreement with [3], [4] and [6]. In figure 5, the minimum total cost corresponds to $D^*=5$, i.e. $(H^*,d^*)=(4,1)$. We also notice that the values of C_T for $(H^*,d^*)=(3,2)$ and $(H^*,d^*)=(2,3)$ are very similar indeed. Intuitively, when D decreases from its optimal value, D^*, the residing area of the MT decreases, and thus increases the LU cost. When D increases from its optimal value, D^*, the residing area of the MT increases, and thus increases the MT PG cost. Figure 5 reflects this behavior. Therefore we can roughly assert that, for a distance threshold D lower than its optimal value, D^*, the main contribution to C_T comes from the LU cost, and, for a distance threshold D higher than its optimal value, D^*, the main contribution to C_T comes from the MT PG cost.

When a two steps PG procedure is applied, see figure 6, the minimum total cost C_T^* is reached for $D^*=6$, $(H^*,d^*)=(5,1)$. Note the reduction of the terminal paging cost at the right side of the optimal value, D^*. Compared with the single step paging of figure 5, cost at

$$
\begin{aligned}
q_{0,i}(a,d) = \sum_{z=0}^{\infty} \alpha(z)\pi_{0,i}(z,d) = & \frac{\sum_{n=0}^{d-1}\alpha(n)p_{H,i}^{(n)} + [\alpha(d) - a^d\alpha(0)][P_{nab}(H,d)p_{0,i}^{(0)} + {}_{H-1}f_{H,H}^{(d)}p_{H,i}^{(0)}]}{R_H^*(a)[1-\sum_{n=1}^{d} a^n \ {}_{H-1}f_{H,H}^{(n)}] - af_{H,H-1}^{(1)}R_{H-1}^*(a) - a^d P_{nab}(H,d)} \\
& - \frac{\sum_{n=1}^{d-1} a^n \ {}_{H-1}f_{H,H}^{(n)} \sum_{k=0}^{d-n-1}\alpha(k)p_{H,i}^{(k)} + af_{H,H-1}^{(1)}\sum_{n=1}^{d-2}\alpha(n)p_{H-1,i}^{(n)}}{R_H^*(a)[1-\sum_{n=1}^{d} a^n \ {}_{H-1}f_{H,H}^{(n)}] - af_{H,H-1}^{(1)}R_{H-1}^*(a) - a^d P_{nab}(H,d)} \\
& - \frac{G_{H,i}^*(a)[1-\sum_{n=1}^{d} {}_{H-1}f_{H,H}^{(n)}a^n] - af_{H,H-1}^{(1)}G_{H-1,i}^*(a)}{R_H^*(a)[1-\sum_{n=1}^{d} a^n \ {}_{H-1}f_{H,H}^{(n)}] - af_{H,H-1}^{(1)}R_{H-1}^*(a) - a^d P_{nab}(H,d)}
\end{aligned} \tag{15}
$$

the left side of D^* in figure 6 remains roughly the same, as it would be expected, since the CMR is the same for both figures. The same comments can be written when a three step paging algorithm is applied, see figure 7. In general, when selective paging is implemented, two general conclusions can be envisaged. First, a highly significant reduction in the expected cost is achieved when the paging delay is increased from $\eta = 1$ to $\eta = 2$. When increasing from $\eta = 2$ to $\eta = 3$ the reduction is however, less spectacular. Second, C_T is less sensitive to the changes of D, around its optimal value, D^*.

Results for $CMR = 0.1$ are given in figures 8, 9 and 10 for paging delay $\eta = 1$, 2 and 3 respectively. Similar conclusions can be derived. Furthermore we realize the fact that when selective paging is implemented ($\eta > 1$) and for large values of D, ($D > D^* - optimum-$), the total cost C_T increases with H. This is due to the fact that when H increases, fewer LUs are produced, which results in less contacts with the network. So, the uncertainty of the MT position increases and as a consequence of this, the MT PG cost increases as well. Finally figures 11, 12 and 13 plot the total cost, C_T, for $CMR = 1$ and paging delay $\eta = 1$, 2 and 3 respectively. We can see that for a given D, C_T practically remains constant for all schemes (M an empty set, and $H = 0$, 1, 2, ..., D-1). On the average, each time the MT visits a new cell a new call is received.

5. Conclusions

In this paper we introduce and analyze an hybrid movement-distance-based strategy for mobility tracking. The decision on LU is dynamically taken when a threshold d is reached by a movement counter which, however, it is reset every time the MT visits a cell that belongs to a not empty set of M cells, located within a given distance H from the cell where the last update occurred. Both parameters are related by $D = H + d$. Our proposal includes, as particular cases, the movement–based scheme (the set of M cells is empty) and the distance–based scheme ($H = D - 1$). Therefore, a trade-off between both strategies has been faced and analyzed. Our results confirm that distance–based scheme produces the best results compared with movement–based strategy. When M is not an empty set, the strategy avoids useless location updates. However it requires that, after each movement, the MT has to search the identity of the new visited cell in a cache memory, and after each location update, the fixed network has to transfer to the MT the identification of a new set of M cells located around its actual position. Results obtained from our analytical model show that, with little memory requirements in the MT very good performances can be obtained, close to the distance–based scheme.

REFERENCES

[1] D. R. Cox, H. D. Miller,"The theory of stochastic process", Chapman-Hall, (Science Paperbacks) 1972.

[2] E. Alonso, K. S. Meier-Hellstern, G. Pollini, "Influence of cell geometry on handover and registration rates in cellular and universal personal telecommunication networks," Proceedings of the 8th ITC Spec. Sem. Universal Pers. Telecommun. pp. 261- 270, October 12- 14, 1992. Santa Margherita Ligure, Genova (Italy).

[3] A. Bar-Noy, I. Kessler, M. Sidi, "Mobile users: To update or not to update", Proceedings of the INFOCOM'94 pp. 570-576, June 14-16, 1994, Toronto, Ontario (Canada).

[4] A. Bar-Noy, I. Kessler, M. Sidi, "Tracking strategies in wireless networks", Proceedings of the IEEE Int. Symp. on Information Theory, pp. 413, June 27- July 1, 1994. Trondheim (Norway).

[5] R. Jain, Y.-B. Lin, C. N. Lo and S. Mohan, "A caching strategy to reduce network impacts of PCS", IEEE J. Select. Areas on Communications, Vol. 12, n. 8 pp 1434-1445, August 1994.

[6] A. Bar-Noy, I. Kessler, M. Sidi, "Mobile users: To update or not to update", ACM-Baltzer Journal of Wireless Networks, Vol. 1, n.2, pp.175-186, July 1995.

[7] C. Rose, R. Yates, "Minimizing the average cost of paging under delay constraints", ACM-Baltzer Journal of Wireless Networks, vol. 1, n.2 pp. 211-219, July 1995.

[8] J. S. M. Ho and I. F. Akyildiz, "Movement user location update an paging under delay constraints", ACM-Baltzer Journal of Wireless Networks, Vol. 1, n.4 pp. 413-425, December, 1995.

[9] I. F. Akyildiz, J. S.M. Ho, Y.-B. Lin, “Movement-based location update and selective paging for PCS networks”, IEEE/ACM Trans. on Networking, Vol. 4, n. 4 pp 629-638, August 1996.

[10] Y.-B. Lin and W. Chen, “Impact of busy lines and mobility on cell blocking in PCS networks,” International Journal of Communication Systems, Vol. 9, pp. 35–45, 1996.

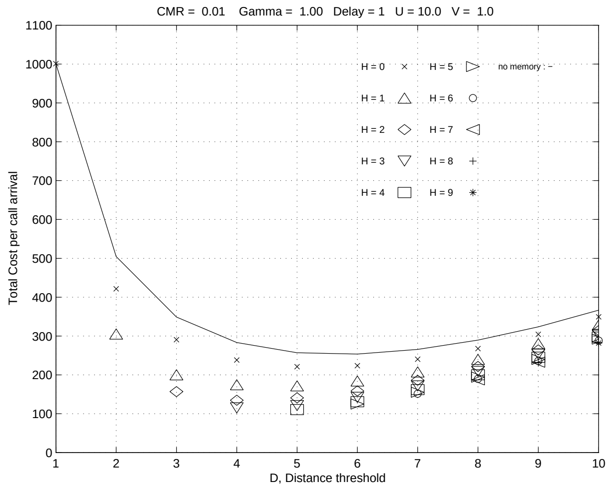
[11] Y.-B. Lin, “Reducing location update cost in PCN”, IEEE/ACM Trans. on Networking, Vol. 5, n. 1 pp 25-33, February 1997. (Submitted for publication in 1993).

[12] M. M. Zonoozi, P. Dassanayake, “User mobility modeling and characterization of mobility patterns”, IEEE J. Select. Areas on Communications, Vol. 15, n. 7 pp 1239 -1252, September 1997.

[13] V. Casares-Giner, J. Mataix-Oltra, “A relationship between movement-based and distance-based location update strategies”. Internal Report. Departamento de Comunicaciones -Universidad Politécnica de Valencia- December 1997.

[14] V. Casares-Giner, J. Mataix-Oltra, “On movement-based mobility tracking strategy. An enhanced version”, IEEE Communications Letters, Vol. 2, n. 2 pp 45-47, February 1998.

[15] Y. Fang, ”Movement-Based mobility management and trade off analysis for wireless mobile networks”, IEEE Trans. on Computers, Vol. 52, n. 6 pp 791-803, June 2003.



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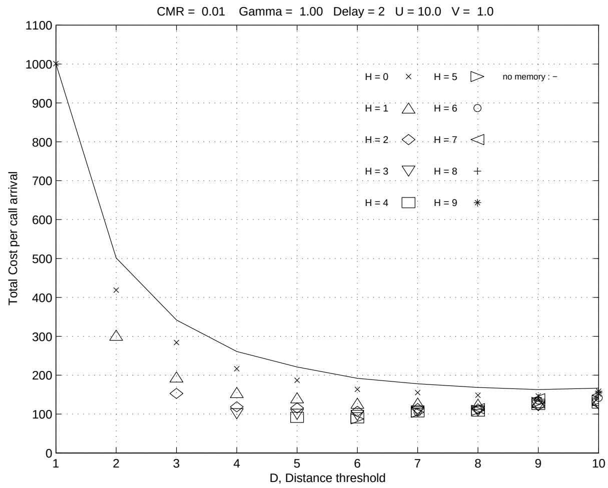

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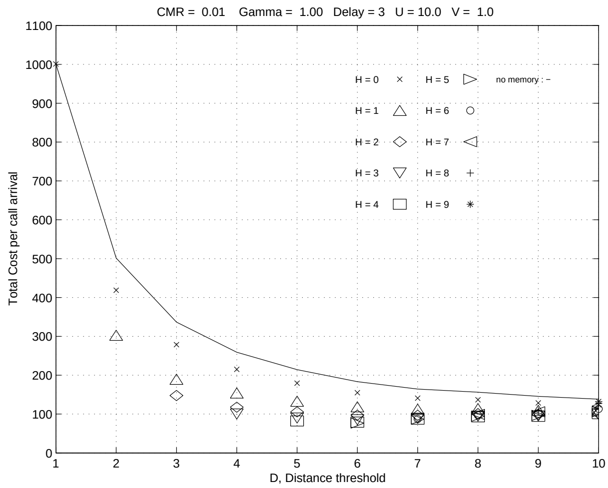
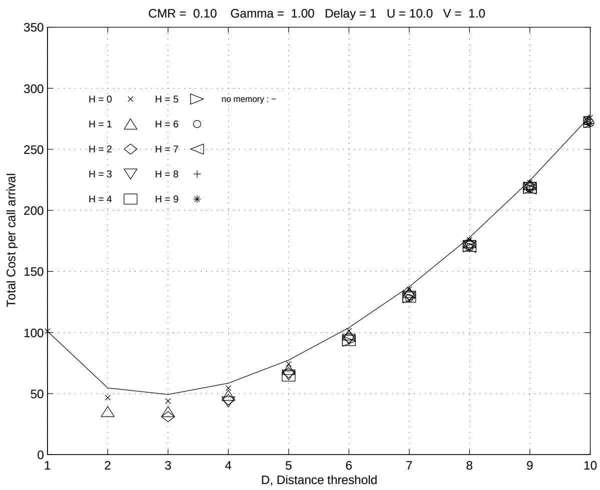


Figure 7.

Figures 5, 6 and 7 show the total cost per call arrival for $CMR = 0.01$, $\gamma = 1$, $U = 10$, $V = 1$, and delay $\eta = 1$, 2 and 3 respectively. Plots are given in terms of the distance threshold D, for each set of points (H, d) such that $H + d = D$.



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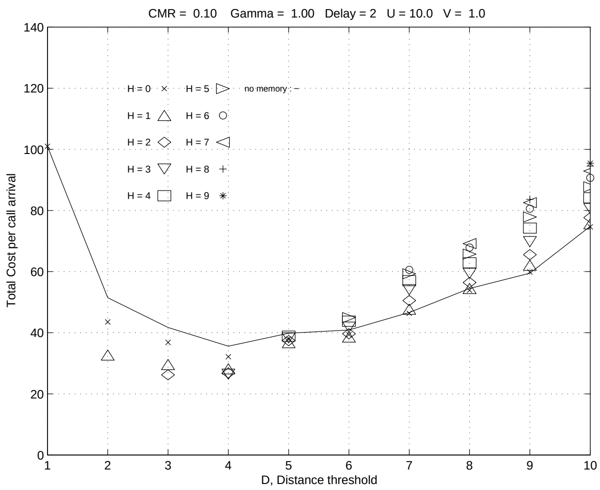

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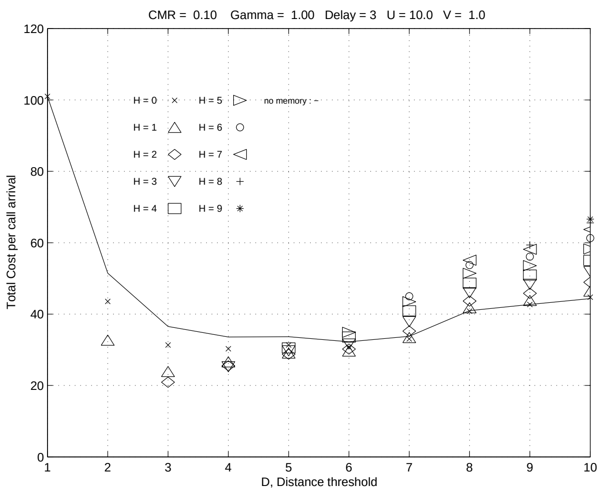


Figure 10.

Figures 8, 9 and 10 show the total cost per call arrival for $CMR = 0.1$, $\gamma = 1$, $U = 10$, $V = 1$, and delay $\eta = 1$, 2 and 3 respectively. Plots are given in terms of the distance threshold D, for each set of points (H, d) such that $H + d = D$.

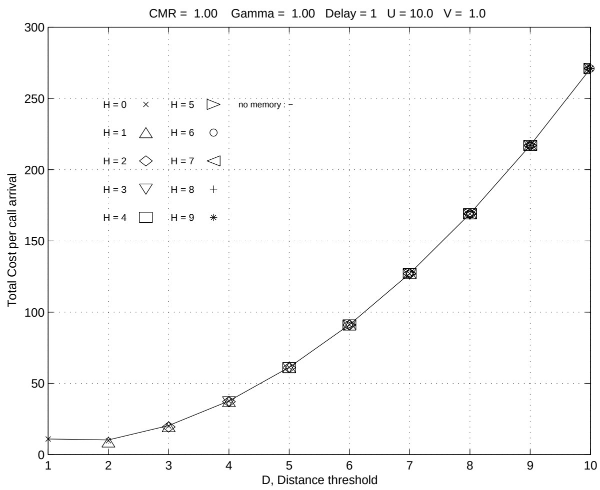
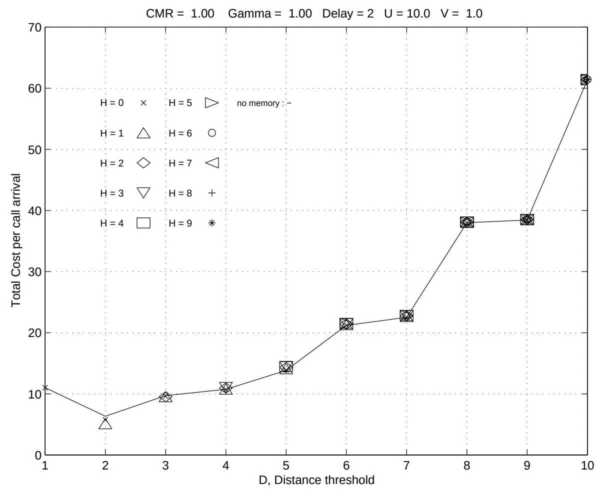


Figure 11.



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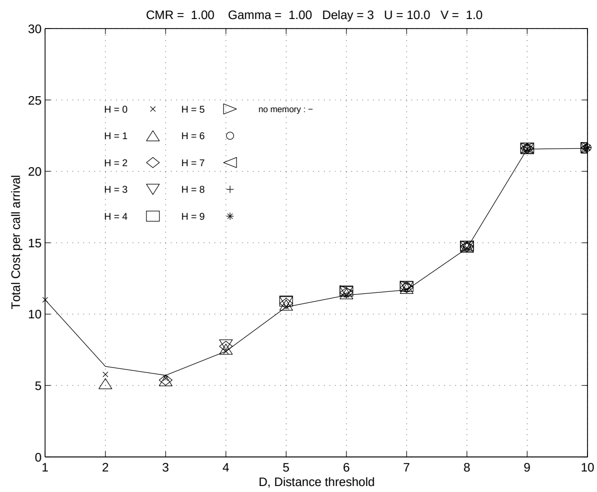

Figure 13.

Figures 11, 12 and 13 show the total cost per call arrival for $CMR = 1$, $\gamma = 1$, $U = 10$, $V = 1$, and delay $\eta = 1$, 2 and 3 respectively. Plots are given in terms of the distance threshold D, for each set of points (H, d) such that $H + d = D$.