# A Dynamic Mobility Tracking Policy for Wireless Personal Communications Networks

**Joseph S.M. Ho and Ian F. Akyildiz**

Broadband and Wireless Networking Laboratory
School of Electrical and Computer Engineering
Georgia Institute of Technology, Atlanta, GA 30332, U.S.A.
E-mail: joseph@ee.gatech.edu; ian@armani.gatech.edu

**Abstract:** *This paper introduces a location update policy which minimizes the cost of mobile terminal (MT) location tracking. An MT dynamically determines when to perform location update based on its mobility pattern and the incoming call arrival probability. The performance of this scheme is close to that of the optimal policy reported earlier. However, the processing time requirement of this scheme is very low. The minimal computation required by this scheme enables its usage in MTs which has limited energy supply and computational power.*

**Key Words:** *PCN, Location Update, Terminal Paging.*

## 1 Introduction

Current Personal Communications Networks (PCNs) employ a cellular architecture such that the PCN coverage area is divided into *cells*. All mobile terminals (MTs) within a cell communicate with other MTs through a base station which is installed within the cell. This base station is connected to other base stations and stationary terminals through an underlying wireline network. In order to route incoming calls, each MT reports its location to the network by a process called *location update*. In current cellular systems, cells are grouped together into *location areas* (LAs). An MT performs location update whenever it enters a new LA. When a call arrives, the network polls each cell of the LA to locate the MT. This polling process is called *terminal paging*.

In this paper, we introduce a dynamic location update mechanism which can be tailored to the mobility and call arrival pattern of each individual MT. The location update decision process is distributed over time. Changes in the call arrival and mobility pattern of an MT are taken into account from time to time while the computational requirement is limited. A number of mobility tracking schemes were reported in [2, 3, 4, 5] and a brief introduction of these schemes can be found in [1]. Most of the previous schemes assume the mobility of the MTs to follow specific models such as the memoryless random walk model [3, 4, 5] or the Markovian model [3]. Our mechanism is not based on a specific assumption on movement pattern. Analytical results demonstrated that the performance of our mechanism stays close to that produced by an optimal policy given in [4] under various movement and incoming call arrival probabilities. Moreover, the performance of our mechanism never falls below that of a no-update policy (location update is never performed). This means that the cost effectiveness of mobility tracking is improved by using the location update policy.

This paper is organized as follows. In section 2, we describe the system model. In section 3 we introduce the proposed dynamic location update mechanism. Section 4 presents the performance evaluation for the dynamic location update mechanism. The conclusion is given in Section 5.

## 2 System Model

### 2.1 Terminal Mobility

We assume that the PCN coverage area is divided into hexagonal cells of the same size such that each cell has six neighbors. Figure 1 shows an example of a PCN coverage area with 61 cells. Our location update mechanism does not require specific assumptions on the mobility pattern of the MTs and any knowledge of specific mobility parameters. However, in order to demonstrate the performance of our mechanism, we use the two-dimensional memoryless random walk mobility model throughout this paper. We assume that $X_t$ is the ID of the cell where an MT is located at discrete time $t$. The MT will stay at cell $X_t$ at time $t+1$ with probability $q$ or it will move to one of the neighboring cells with probability $p$, where $p + q = 1$. We also assume that if the MT moves to one of the neighboring cells, there is equal probability, i.e., $\frac{1}{6}$, that any one of the neighboring cells is selected.

It can be seen in Figure 1 that each cell is surrounded by rings of cells. The inner-most ring consists of only one cell (cell 0 in Figure 1) and we call this the center cell. Ring 0 is surrounded by ring 1 (consisting of all cells labeled '1' in Figure 1) which, in turn, is surrounded by ring 2 (consisting of all cells labeled '2' in Figure 1), and so on. For a given center cell, we assume $r_i$ ($i \geq 0$) is the set of all cells in the $i^{th}$ ring. In this paper, all distances are measured in terms of the number of rings such that the distance from a selected center cell to the cells belonging to set $r_i$ is $i$ rings. For example, the distance of the center cell (ring 0) to each cell in ring 4 as indicated in Figure 1 is 4 rings.

We denote the interarrival times of incoming calls by $T$. Assuming that $T$ is a generally distributed iid random variable with probability distribution function $F(t)$ and mean $1/\lambda$.

### 2.2 Mobility Tracking

The PCN has the current location information of an MT after each location update and terminal paging. We assume that the location of each MT is recorded in a database which is updated whenever current information is available. This database update process is called *location registration*. In order to determine if a called MT is located in a particular cell when a call arrives, the network performs the following:

1. Sends a polling signal to the target cell and waits until a timeout occurs.
2. If a reply is received before timeout, the called MT is located in the target cell.
3. If no reply is received, the called MT is not in the target cell.

We define the *center cell* to be the cell where the MT's last location registration occurred. When an incoming call arrives, the PCN polls the cells in the vicinity of the center cell in a shortest-distance-first order. For example, in the PCN coverage area given in Figure 1, we assume that the called MT is located at ring $r_3$ and cell 0 is the center cell of the MT. The PCN will poll the rings in the following order: $r_0$, $r_1$, $r_2$, $r_3$. The network polls a ring by sending a polling signal to all cells in the ring. In this case, the number of cells polled before the MT is found is 37. In general, given that an MT

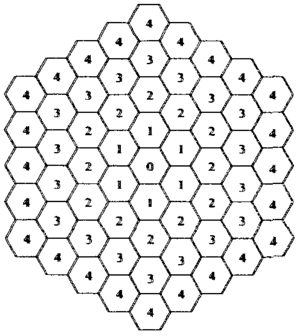

Figure 1: Two-Dimensional PCN Coverage Area.

is located in ring $r_k$ the number of cells polled before the MT is successfully located is:

$$h(k) = 3k(k+1) + 1$$

We assume that when an incoming call arrives, the network is able to locate the called MT within the same discrete time period. The following is an ordered list of tasks that an MT performs within each discrete time period:

1. Determine if the location of the MT is changed as compared to its location during the previous discrete time period.
2. If the location of the MT is changed, calculate the next location update time.
3. If an incoming call is pending, receive the call and set the location update time to infinity (no location update is necessary until the next movement).
4. If current time is bigger than or equal to the next location update time, perform location update and set next location update time to infinity.

A method for determining the next location update time is given in Section 3. The operation of the MT during a call is not considered here and the above list is valid only when no call is currently in progress. For the rest of this paper, we assume that the time is always expressed in the number of discrete time periods. We will not explicitly indicate the unit of time hereafter.

# 3 Dynamic Location Update

We assume that the cost for each location update, denoted by $U$, is independent of the location of the MT. We also assume that the cost for terminal paging is proportional to the number of cells polled before the MT is found. Given that the MT is currently located in ring $r_k$, the cost for terminal paging is:

$$Q(k) = Vh(k) \tag{1}$$

where $V$ represents the cost for polling a particular cell. It is clear that if the arrival time of the next incoming call is known in advance, the MT should perform a location update right before the call arrival if the cost for location update is less than the paging cost ($U < Q(k)$) at that time. Otherwise, no location update should be performed because the paging cost is lower than the location update cost. In reality, we do not know in advance the arrival time of each incoming call. However, given the incoming call interarrival times distribution function, $F(t)$, and the time elapsed since the last call arrival, we can determine the probability distribution of the residual call arrival time. Assuming that $T$ is the incoming call interarrival time with distribution $F(t)$ and $t_e$ is the time elapsed since last call arrival. The probability of an incoming call arrival within the next $\Delta t$ time units is:

$$G(\Delta t, t_e) = \frac{F(\Delta t + t_e) - F(t_e)}{1 - F(t_e)}$$

Since the cumulative probability of call arrival increases with time, the risk of not updating the location also increases with time. We define the weighted paging cost $\Delta t$ time units from the current time as:

$$W(\Delta t, t_e, k) = G(\Delta t, t_e)Q(k) \tag{2}$$

The weighted paging cost at a given time interval from the current time is the terminal paging cost multiplied by the probability of call arrival during that time interval. As it can be seen in equation (2), the weighted paging cost increases with time. Its value approaches that of the paging cost, $Q(k)$, as the time interval, $\Delta t$, increases. The weighted paging cost, therefore, takes into account of the increasing probability of having to pay the terminal paging cost as time advances. A location update should be performed at the time when the weighted paging cost exceeds the location update cost. We propose a location update mechanism which determines the time of the next location update based on the call interarrival time distribution function, $F(t)$, the distance traveled since the MT's last location registration, $k$, and the time elapsed since the last call arrival, $t_e$. The following equation gives the weighted paging cost on the left hand side and the location update cost on the right hand side:

$$G(\Delta t, t_e)Q(k) = U \tag{3}$$

Given the values of $k$ and $t_e$, the time until the next location update, $\tau(k)$, can be determined by solving equation (3) for $\Delta t$:

$$\tau(k) = \{\Delta t \mid G(\Delta t, t_e)Q(k) = U\}$$

Since the probability $G(\Delta t, t_e)$ can never exceed 1, equation (3) is valid only when $U \le Q(k)$. When $U > Q(k)$, the weighted paging cost, $W(\Delta t, t_e, k)$, can never exceed the location update cost, $U$. No location update is necessary under this situation, i.e., $\tau(k) = \infty$. As the distance, $k$, changes when the MT moves to another ring, $\tau(k)$ is updated. Assuming that the MT moved to the current ring at time $t_m$ and the distance of the MT from its center cell is $k$. The next location update time is:

$$t_u = t_m + \tau(k) \tag{4}$$

If the MT moves to another ring before $t_u$, a new value for $t_u$ will be determined based on the up-to-date distance $k$ and the time elapsed since the last call arrival $t_e$. The proposed location update mechanism is summarized as follows:

1. The following information is collected whenever the MT enters a ring: i) the distance traveled since the last location registration, $k$, ii) the cost for the network to page for the MT, $Q(k)$, and iii) the time elapsed since the last call arrival, $t_e$.
2. Using the data obtained in the previous step, determine the time until next location update, $\tau(k)$, by solving equation (3) for $\Delta t$.
3. Record the $\tau(k)$ value obtained in the previous step and initiate a location update at time $t_u = t_m + \tau(k)$.

## 3.1 Geometric Call Interarrival Time Distribution

Here we consider the special case where the call interarrival time distribution is geometric. Based on this assumption, we

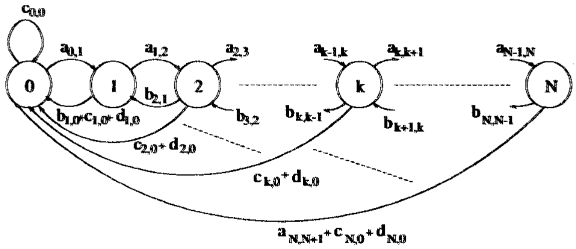


Figure 2: State Transition Diagram.

develop the expression for the time until next location update, $\tau(k)$. The probability distribution of call interarrival time is:

$$F(t) = 1 - (1-\lambda)^t \tag{5}$$

Because of the memoryless property of the geometric distribution, the residual call arrival time is independent of the time elapsed since the last call arrival. As a result, the probability distribution of the residual call arrival time given the time elapsed since the last call arrival, $t_e$, is the same as $F(t)$ given in equation (5):

$$G(\Delta t, t_e) = 1 - (1-\lambda)^{\Delta t} \tag{6}$$

Substituting equation (6) in equation (3) and solving for $\Delta t$, the next location update time, $\tau(k)$, is:

$$\tau(k) = \begin{cases} \infty & \text{if } k = 0 \\ \infty & \text{if } U \geq Q(k) \\ \lfloor \log_{(1-\lambda)}(1 - \frac{U}{Q(k)}) \rfloor & \text{otherwise} \end{cases} \tag{7}$$

A $\tau(k)$ value of $\infty$ indicates that no location update is necessary. As can be seen from equation (7), no location update is needed either when $k = 0$ or when $U \geq Q(k)$. The first case represents the situation right after a location registration. The network knows exactly the location of the MT. No location update is therefore needed until after the next movement. In the second case, the location update cost is always higher than or equal to the weighted paging cost no matter what the probability weighting, $G(\Delta t, t_e)$, is. It is therefore more economical not to perform any location update. The next location update time, $t_u$, is computed from equation (4).

# 4 Performance Evaluation

## 4.1 Analytical Model

Here we develop an analytical model for the dynamic location update mechanism based on the random walk mobility model and the geometric call interarrival time distribution. We capture the activity of an MT using an Imbedded Markov chain (see Figure 2) of which the state $i$ ($i \geq 0$) is defined as the distance between the current location of the MT and its center cell. State transitions of the Imbedded Markov chain occurs right after: 1) a movement to one of the neighboring cells, 2) a call arrival or 3) a location update. The transition probabilities $a_{i,i+1}$ ($0 \leq i \leq N$) and $b_{j,j-1}$ ($0 < j \leq N$) represent the movement of the MT to a neighboring cell such that its distance from the center cell is increased or decreased, respectively. The transition probabilities $c_{i,0}$ ($0 \leq i \leq N$) represent the arrival of incoming calls when the MT is $i$ cells away from the center cell. The transition probabilities $d_{i,0}$ ($0 < i \leq N$) represent location updates performed when the MT is $i$ cells away from its center cell.

It can be seen in equation (7) that the location update time interval $\tau(k)$ decreases as the distance $k$ increases. The average time at a state, $k$, is zero if $\tau(k) = 0$. This is because every transition into this state will result in an instantaneous transition to state 0 because of a location update. The highest state of the Imbedded Markov chain, $N$, can be determined by finding the $N$ value such that:

$$\tau(N) > 0$$
$$\tau(N+1) = 0$$

The transition $a_{N,N+1}$ in Figure 2 represents an increase of the MT's distance from $N$ to $N+1$. This movement results in an immediately location update which changes the state of the MT from $N+1$ to 0 instantly.

Let $M$ and $T$ be two geometrically distributed iid random variables which represent the inter-movement time and the call interarrival time, respectively. As described before, $p$ and $\lambda$ denote the movement probability and the call arrival probability, respectively. We define $\gamma$ as:

$$\gamma = 1 - \lambda \tag{8}$$

According to the mobility model given in Figure 1, movement of the MT may not always result in a change of its distance from the center cell. When the MT is residing in a ring other than ring $r_0$, the probability that a movement will result in a change of the distance from the center cell is $\frac{2}{3}$. Given that an MT is residing at ring $r_k$, the probability that the MT will move to another ring during each discrete time period is:

$$x_k = \begin{cases} p & \text{for } k = 0 \\ \frac{2}{3}p & \text{for } k > 0 \end{cases}$$

We further define $y_k$, $\alpha_k$ and $\beta_k$ as:

$$y_k = 1 - x_k \tag{9}$$

$$\alpha_k = y_k \gamma \tag{10}$$

$$\beta_k = 1 - \alpha_k \tag{11}$$

Given that an MT is located at ring $r_k$, the probability that its next movement to another ring will result in an increase of its distance from the center cell is:

$$\rho_k = \frac{1}{2} + \frac{1}{4k}$$

The probability that a movement to another ring occurs before the arrival of a call ($Pr[M < T]$) is:

$$\theta_k = \frac{x_k \gamma}{1 - y_k \gamma}$$

According to the ordered list of tasks performed by an MT given in Section 2.2, we assume that if both a movement and a call arrival occur at the same discrete time period, the movement is performed before the call is received. This means that if an MT is at state $k$ when both movement and call arrival occur, the next state of the MT is 0. We further assume that if either the movement time or the call arrival time coincide with the location update time, the location update will not be performed. A new location update time will be selected after the movement or the call is complete. Since the probability that more than two events occur at the same time is low when the discrete time period is small, the effect of the above assumptions to the analytical result is minimal. The state transition probabilities of the Imbedded Markov chain are:

For $\tau(k) = \infty$:

$$a_{k,k+1} = \begin{cases} \theta_k & \text{for } k = 0 \\ \theta_k \rho_k & \text{for } k > 0 \end{cases}$$

$$b_{k,k-1} = \theta_k(1-\rho_k)$$
$$c_{k,0} = 1-\theta_k$$
$$d_{k,0} = 0$$

For $\tau(k) < \infty$:

$$a_{k,k+1} = \rho_k\left\{\gamma^{\tau(k)}(1-y_k^{\tau(k)}) + \lambda\left[\frac{\gamma(\gamma^{\tau(k)-1}-1)}{\gamma-1} - \frac{\alpha_k(\alpha_k^{\tau(k)-1}-1)}{\alpha_k-1}\right]\right\}$$

$$b_{k,k-1} = (1-\rho_k)\left\{\gamma^{\tau(k)}(1-y_k^{\tau(k)}) + \lambda\left[\frac{\gamma(\gamma^{\tau(k)-1}-1)}{\gamma-1} - \frac{\alpha_k(\alpha_k^{\tau(k)-1}-1)}{\alpha_k-1}\right]\right\}$$

$$c_{k,0} = y_k^{\tau(k)-1}(1-\gamma^{\tau(k)}) + \frac{x_k}{y_k}\left[\frac{y_k(y_k^{\tau(k)-1}-1)}{y_k-1} - \frac{\alpha_k(\alpha_k^{\tau(k)-1}-1)}{\alpha_k-1}\right]$$

$$d_{k,0} = (y_k\gamma)^{\tau(k)}$$

Assuming $p_k$ is the equilibrium probability of state $k$. The balance equations can be obtained as:

$$a_{0,1}p_0 = b_{1,0}p_1 + a_{N,N+1}p_N + \sum_{j=1}^{N}(c_{j,0}+d_{j,0})p_j \quad \text{for } N > 0 \tag{12}$$

$$p_k = a_{k-1,k}p_{k-1} + b_{k+1,k}p_{k+1} \quad \text{for } 0 < k < N \tag{13}$$

$$p_N = a_{N-1,N}p_{N-1} \quad \text{for } N > 0 \tag{14}$$

The equilibrium probability of each state can be expressed in terms of the equilibrium probability of state $N$ as:

$$p_k = \eta_k p_N \qquad \text{for } 0 \le k < N \tag{15}$$

where $\eta_k$ is the ratio of the equilibrium probabilities of states $k$ and $N$. The probability of state $N$ can then be solved by applying the law of total probabilities as:

$$p_N = \frac{1}{1+\sum_{j=0}^{N-1}\eta_j} \qquad \text{for } N > 0 \tag{16}$$

The equilibrium state probability of states $k$ can be obtained by substituting equation (16) into equation (15). Equations (12) through (16) are valid only when $N > 0$. When there is only one state (i.e. $N = 0$), the equilibrium state probability of state 0 is equal to 1 ($p_0 = 1$). Assume $S'_u$ and $S'_v$ are the cost for location update and terminal paging per state transition, respectively. The expressions for $S'_u$ and $S'_v$ are:

$$S'_u = \begin{cases} U a_{0,1} & \text{if } N = 0 \\ U(p_N a_{N,N+1} + \sum_{j=1}^{N} p_j d_{j,0}) & \text{if } N > 0 \end{cases}$$

$$S'_v = \begin{cases} c_{0,0}[x_k Q(1) + y_k Q(0)] & \text{if } N = 0 \\ p_0 c_{0,0}[x_k Q(1) + y_k Q(0)] + \sum_{j=1}^{N} p_j c_{j,0} \times \\ \{y_j Q(j) + x_j[\rho_j Q(j+1) + \\ (1-\rho_j)Q(j-1)]\} & \text{if } N > 0 \end{cases}$$

Let $\pi_k$ be the *average sojourn time* of state $k$ which is the smallest of three time intervals: the deterministic update time $\tau(k)$, the residual incoming call arrival time and the time until next movement. The expression for $\pi_k$ is:

$$\pi_k = \begin{cases} \tau(k)\alpha_k^{\tau(k)} + \frac{\beta_k}{(\alpha_k-1)^2} \times \\ \left[\tau(k)\alpha_k^{\tau(k)+1} - (\tau(k)+1)\alpha_k^{\tau(k)} + 1\right] & \text{if } \tau(k) < \infty \\ \frac{1}{\beta_k} & \text{if } \tau(k) = \infty \end{cases}$$

where $\tau(k)$, $\alpha$ and $\beta$ are computed from equations (7), (10) and (11), respectively. The *average time between state transitions*, $\mu$, is:

$$\mu = \sum_{j=0}^{N} p_j \pi_j$$

The *total location update and terminal paging cost* is:

$$S_T = \frac{S'_u}{\mu} + \frac{S'_v}{\mu} \tag{17}$$

## 4.2 Performance Bounds

We will compare the performance of the proposed dynamic policy with a *no-update policy* and an *optimal policy* [4, 5] as described below:

**No-update policy**: No location update is performed under this policy. When a call arrives, the network searches for the MT starting from the cell where the last call arrival occurred. Since the purpose of location update is to reduce the cost for tracking down the MT, an effective location update policy should reduce the average cost as much as possible compared to the no-update policy.

**Optimal policy**: A location update is performed when the MT's distance from the cell where the last location registration occurred exceeds an optimal distance. The optimal location update distance is selected based on the mobility and call arrival parameters such that the total location update and terminal paging cost is minimized.

Given the no-update and the optimal policies, we expect the average cost of the proposed location update mechanism to be close to that of the optimal policy while, at the same time, it must never exceed that of the no-update policy. We denote the average costs of the no-update and the optimal policies by $S_T^n$ and $S_T^*$, respectively. The algorithms for determining $S_T^n$ and $S_T^*$ based on the system parameters such as the call arrival and the movement probabilities are reported in [1, 4] and is not discussed here due to space limitation.

## 4.3 Analytical Results

Figures 3(a), 3(b) and 3(c) show the average cost, $S_T$, for location update costs, $U$, of 1, 10 and 50, respectively. The call arrival probability, $\lambda$, and the polling cost, $V$, are fixed at 0.01 and 1, respectively, while the probability of moving, $p$, varies from 0.001 to 0.5. When $U = 1$ (Figure 3(a)) there is a big difference between the average cost of the optimal, $S_T^*$, and that of the no-update policies, $S_T^n$. This means that the gain from performing location update is significant. It can be seen that $S_T$ is very close to $S_T^*$ while it is significantly lower than $S_T^n$. When $U = 10$ (Figure 3(b)) the difference between $S_T^*$ and $S_T^n$ reduces. The values of $S_T$ are very close to $S_T^*$ for all movement probability, $p$, values. When $U = 50$ (Figure 3(c)) the $S_T$ is about half way between $S_T^*$ and $S_T^n$. Figures 4(a), 4(b) and 4(c) show similar results when $p$ is

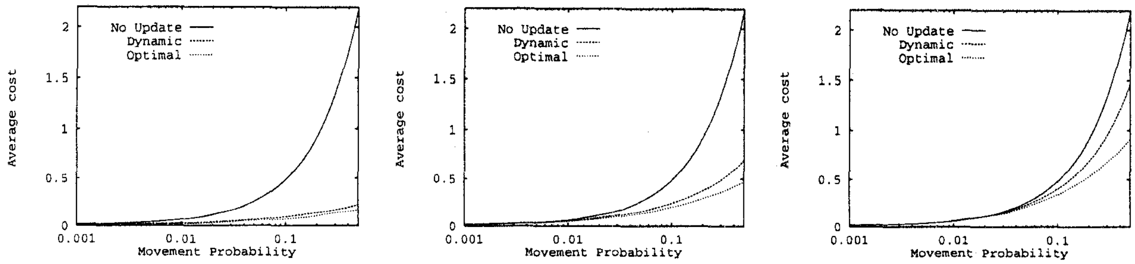


Figure 3: Average Cost vs Movement Probability for (a) $U = 1$ (b) $U = 10$ and (c) $U = 50$.

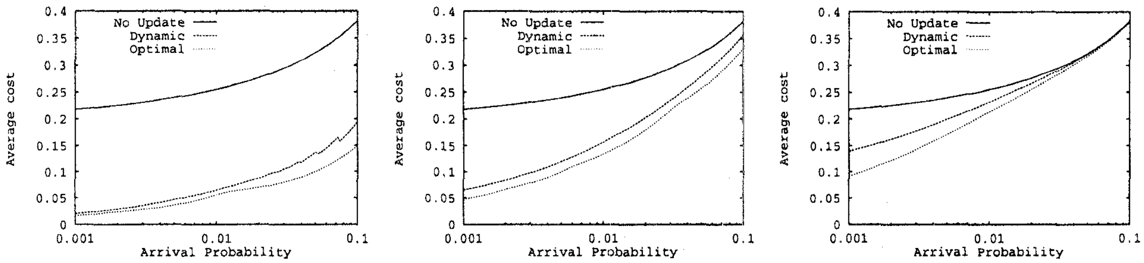


Figure 4: Average Cost vs Call Arrival Probability for (a) $U = 1$ (b) $U = 10$ and (c) $U = 50$.

fixed at 0.05 while $\lambda$ varies from 0.001 to 0.1. When $U = 1$ (Figure 4(a)) the difference between $S_T^*$ and $S_T^n$ is large. The values of $S_T$ is only slightly higher than that of $S_T^*$ for all values of $\lambda$ considered. When $U = 10$ (Figure 4(b)), the difference between $S_T^*$ and $S_T^n$ reduces as $\lambda$ increases. For all values of $\lambda$ considered, $S_T$ is very close to $S_T^*$. When $U = 10$ (Figure 4(c)) the three curves overlap each other when $\lambda$ is large. The values of $S_T$ is close to that of $S_T^*$.

Figure 5 shows the average cost as the location update cost, $U$, varies from 0.1 to 100. The movement probability, $p$, the call arrival probability, $\lambda$, and polling cost, $V$, are set to 0.05, 0.01 and 1, respectively. It can be seen that the average cost of the no-update policy, $S_T^n$, is constant for all values of $U$. As no location update is performed by the no-update policy, $S_T^n$ is independent from changes in $U$. The average costs for both the dynamic and the optimal policies increase as $U$ increases. For $U = 100$, the costs for all three policies are close to each other. For all values of $U$ considered, $S_T$ is close to $S_T^*$.

These results demonstrated the ability of the dynamic location update mechanism to adjust to changes in system parameters to minimize cost. In most cases, the average cost of the dynamic policy is close to that of the optimal policy. While it requires significant computation to achieve the optimal cost (as demonstrated in [4, 5]), the dynamic policy generates near-optimal performance at much lower computational cost. Under all the parameters considered, the average cost of the dynamic policy is always lower than that of the no-update policy.

# 5 Conclusions

A dynamic location update policy is introduced in this paper which can adjust to changes in system parameters, such as the call arrival probability and the mobility pattern of the mobile terminal (MT), to attain better cost effectiveness. The computational overhead of our policy is low and the required processing is distributed over time. Analytical results demonstrated that the dynamic policy can generate similar performance as the optimal policy given in [4]. Moreover, application of the dynamic policy is not restricted for a specific assumption on the mobility pattern of the MTs.

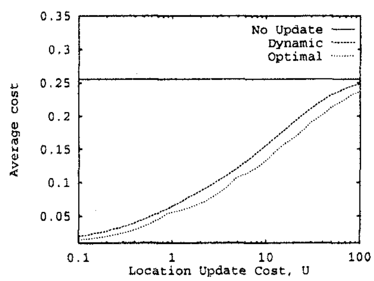


Figure 5: Average Cost vs Location Update Cost, $U$.

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