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A Hierarchical Mobility Management Technique for Wireless Cellular Networks

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Abstract

Mobility Management is one of the major functions of wireless networks to allow mobile terminals (MTs) to stay connected. The aim of mobility management is to track where MTs are, so that calls and other services can be delivered to them. In this paper, we suggest a complete framework for mobility management in hierarchical cellular networks (HCNs), where MTs receive signal from both micro and macro cell tiers. It takes into account the dynamic factors for location area update along with a cost effective paging strategy suitable for HCNs. Comparative performance analyses indicate that this new technique outperforms the basic techniques (originally proposed for HCNs) considerably in terms of both signaling cost and delay.

Keywords: *Mobility management, hierarchical cellular networks, macro/micro paging, dynamic location update.*

1. Introduction

Current cellular networks usually partition their coverage areas into a number of location areas (LAs). Mobile terminals (MTs) typically perform location updates when they cross LA boundaries. Each LA consists of a group of cells. Paging is the search process to find a desired MT when a call arrives for it. Mobility management (MM) using paging and LA update (LAU) aims for fast, cost effective techniques.

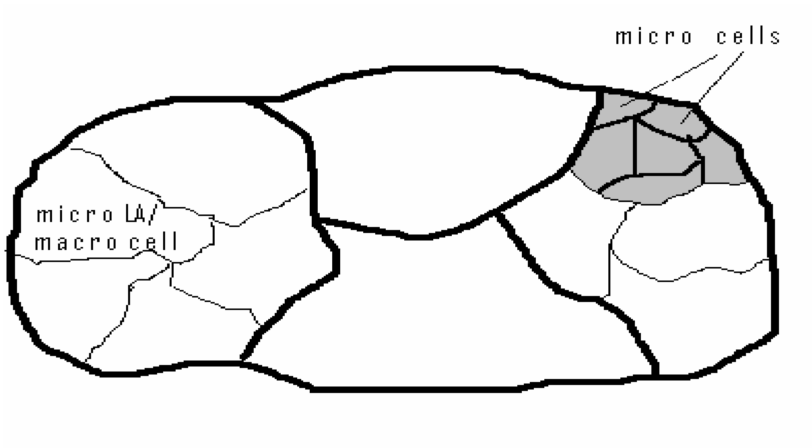

Figure 1. LA structure in Hierarchical Cellular Networks

The high demand for personal communications is driving new network concepts, such as overlaying macro/micro cells, leading to hierarchical cellular networks (HCNs) [1]. Macro cells are rather large (up to 35 km around the base station), whereas micro cells are much smaller (at most 1 km around base station). In HCNs, normally a macro cell contains the exact number of micro cells that belong to a micro LA (Figure 1). MTs receive signal from both the tiers. This paper addresses some key mobility management parameters of HCNs, giving rise to an MM technique (MMT) that reduces both cost and latency. It uses dynamic LAU [2] along with separated macro-micro paging (SMMP) [9]. To the best of our knowledge, no previous work attempted to combine SMMP with dynamic LAU, though individually each technique has been shown to work with HCNs.

2. Background

The usual strategies for LAU in single tier networks are normal LAU (NLAU) or periodic LAU (PLAU) (Figure 2). NLAU [3] is a static location update strategy, where the buffered location information of the MT is only updated if an LA boundary is crossed. If the MT faces a check point event such as abnormal detachment or battery failure, it is not registered. Thus, initial trunk setup cost maybe wasted. A check point is defined as an action to inform the network whether the MT is attached. An incoming or an outgoing call, or NLAU will trigger a checkpoint action. PLAU [4] is a location update strategy where irrespective of the change in the LA boundary, the location information is updated in the register, which may cause unnecessary overhead.

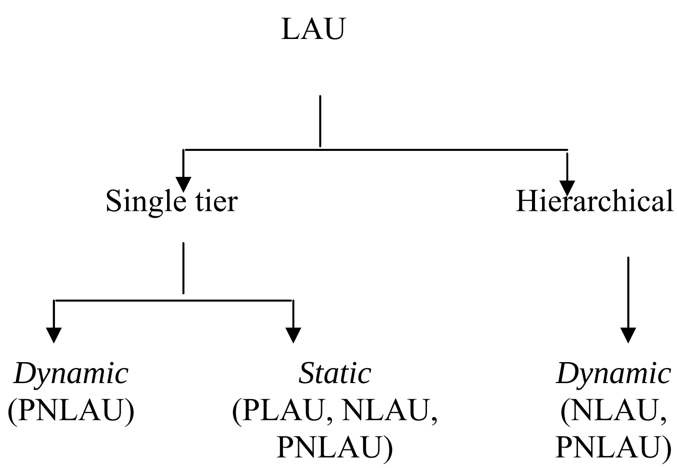

Figure 2. Classification of LAU Techniques

The combination of the above two schemes, PNLAU [2], needs the synchronization of the implicit detach timer, maintained by the network and the identification timer maintained by the MT. These two are set with the length T'. But the frequency of these actions can not be predicted. So, a dynamic method is needed. The dynamic PNLAU chooses a T' such that:

$$T' = v(t_1 + t_2 + t_3 + \dots\dots\dots + t_k)/k, \quad (1)$$

where v is the weighting factor and t_i (i= 1, 2, 3, …., k) is the time interval between two check point events.

The two issues served by the optimal PNLAU [2] are minimization of (a) total cost of signaling and (b) failure rate of call set up. But optimal PLAU is only cost effective in single tier cellular networks. The signaling cost for maintaining an LAU strategy that is dynamic as well as optimal (where delay is concerned), is very high. Even with the prospect of low paging cost for LAU with the change of each micro LA, the total cost still remains very high. Thus, a dynamic location area update strategy, suited for a hierarchical cellular network is needed.

Many LAU/paging combinations have been proposed previously in literature. However, not only most of them are suitable only for single tier cellular networks, but either they overlook the cost parameters or the time constraints. For instance, in [5], a method for minimizing cost in wireless system with delay constraints is proposed, but it works in single tier systems. Similarly, in [6], another LAU/paging strategy is used for single tier systems, which combines three-location area with selective paging. In [1], movement based LAU is combined with sequential paging strategy, but neither does it consider optimal paging cost nor the dynamic parameters for location update. Optimal paging strategies, such as intelligent sequential paging [7] or sectional paging strategy [8], are suitable only for single tier systems. So we believe that SMMP [9] is an appropriate choice for HCNs because here two Paging Waiting Queues (PWQ) are implemented for load balancing.

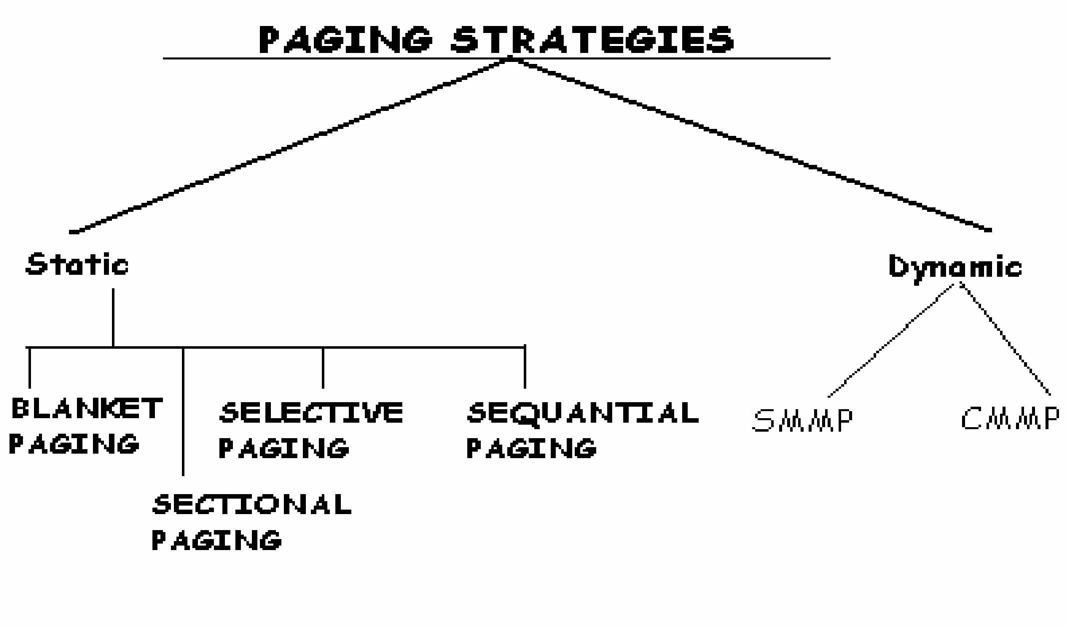

Figure 3. Classification of Paging Strategies

3. Proposed MMT

We suggest a novel LAU/paging complementation in the proposed approach (called MMT_4 in this paper). It combines the characteristics of optimal paging load balance in a hierarchical LA structure [9] with the positive features offered by the dynamic PNLAU [2]. The dynamic PNLAU is, however, modified so as to suit a hierarchical cellular environment. It is called PNLAU* in this work. It is better suited for HCNs because the signaling cost for dynamic LAU for the change of every micro LA boundary is much lower than the optimal LAU strategy. Though MTs receive signals from both micro cell and overlaid macro cell tiers, LAU is operated in macro cell tier only. MTs are, however, paged either in micro cell tier or macro cell tier, depending on the call traffic. SMMP is much more cost effective because of the paging load balance suited for HCNs. Also, LAU cost is reduced owing to the fact that the macro LAs are comparatively larger and less number of updates is needed. Thus, not only this new strategy has the flexibility but it is also dynamic and cost effective. The algorithm for the proposed MMT_4 is given in Appendix I.

We now describe the evolution of MMT_4 from basic techniques. Traditional techniques of single tier networks can be are operated in either micro or macro cell tier only. But they may either be cost effective or take less time, but not both. In fact, we first investigated with applying the conventional LAU/paging to micro cell tier only and then to macro cell tier only (called MMT_1 in this paper). In MMT_1, MTs have to listen only to the macro cell's broadcast channels. An LAU is processed only when an MT crosses a macro LA boundary. Here, the signaling cost is less because LAU is done only when macro LA boundary (a rather large area, so MT takes more time before changing it) is crossed but a large number of MTs has to be paged gives rise to huge paging delay.

The second technique we tried next (called MMT_2) deals with a movement based LAU and a sequential paging strategy. MTs receive signals from both the micro and macro cell tiers because it is in a hierarchical cellular system. LAU happens in the macro cell tier. Paging is done either in the micro cell or the macro cell tier depending on the page load. The macro cell tier is divided into micro Las, and micro cell tier is divided into micro LAs. Each LA has a fixed boundary.

The third technique in the evolutionary path (called MMT_3) combines optimal PLAU with sequential paging strategy. Though the optimal strategy is dynamic and has very small delay, the signaling cost is found to be very high if LAU is done with the change of every micro LA boundary. In comparison to MMT_4, this method is found to be costly in HCNs (discussed in Section 5). So next we formulate MMT_4.

Let us explain MMT_4 with the help of a concrete example. Suppose there are 4 macro LAs, namely LA_1, LA_2, LA_3 and LA_4, and each macro LA_i contains 10 micro LAs, namely LA_{i1}, LA_{i2}, …, and LA_{i10}. If an MT moves from LA_{i1} to LA_{i2}, there will be no new registration. If a checkpoint event, such as an incoming call, occurs the location register would connect the call at the previously registered location. For paging purpose, the micro cells are grouped into micro partition areas (PAs) and the macro cells are grouped into macro PAs. Let each PA contain two cells. Since the paging strategy adopted is SMMP, the paging message will wait either in the micro paging queue or in the macro paging queue (randomly with a probability p or (1-p), respectively). The message will be paged in the entire partition area, i.e., in this case in the entire region LA_{i1} and $LA_{i2.}$ The paging message would be executed in FIFO manner.

Now, if before the checkpoint event the MT changes LA, (i.e., it moves from LA_{11} to $LA_{21,}$ an LAU will take place. If the MT is abnormally detached before the LAU, initial trunk set up cost would be wasted. If, however the LAU is done prior to the incoming call, the channel would be set up as per the new LAU and the paging message would be sent in the new PA.

4. Cost analysis

The cost of LAU/paging process is mainly the cost of bandwidth consumption in the wireless channels and the signaling exchange in the core network. Along with cost, another important factor for HCNs is the delay and the call dropping probability. We present the final results here in terms of them, and the initial analysis is given in Appendix II.

Let p_{ua} denote the probability that there is at least one LAU between two consecutive calls to an MT. Then,

$$p_{ua} = p[t2 > t1] = \mu_{ma} /(\mu_{ma} + \mu_c) \qquad (2)$$

The total cost (signaling and paging) T_1 in MMT_1 is:

$$T_1 = M_a w_{pa} + A_{T2} w_{ua} \qquad (3)$$

where M_a denotes the number of macro cells,$A_{T2} = p_{ua} /(1- p_{ua})^2$; w_{ua} and w_{pa}, (w_{ui} and w_{pi}) denote the LAU and paging cost, respectively, for macro (micro) cell tiers respectively (a=macro; i=micro).

For MMT_2 the total cost is given by T_2,

$$T_2 = M_a w_{pa}(1 - p(Q)) + (M_a+1)/2)M_i W_{pi} p(Q) + A_{T1} W_{ua} \quad (4)$$

where M_i denotes the number of micro cells.

Now, for MMT_3, the cost denoted by T_3 is:

$$T_3 = M_a W_{pa}(1 - p(Q)) + (M_a+1)/2)M_i W_{pi} p(Q) + C_{op} \quad (5)$$

Here, p(Q) is the probability that an MT has to be paged in the micro LA, when all the Q queuing positions are filled in the overlaid macro LA. C_{op} is the total cost involved per check pointing event for the optimal PNLAU scheme [2]:

$$C_{op} = \mathbf{C}_{NLAU} + \mathbf{C}_{PLAU} + \mathbf{C}_{INIT} \quad (6)$$

where, $\mathbf{C}_{NLAU} = C_{nlau}\, n_{nlau} / r$,

$\mathbf{C}_{PLAU} = C_{plau}\, E(N_{plau})$,

$\mathbf{C}_{INIT} = \gamma\, C_{init}$

C_{nlau} and C_{plau} are the signaling cost for NLAU and PLAU, respectively. C_{init} is the cost of initial setting up of network. n_{nlau} is the normal LAU rate; r is the total rate of checkpoint events; γ is the probability that between two checkpoint events the MT is abnormally detached.

For the system to be cost effective LAU is done only with the change of every micro LA boundary, and the strategy used takes into account all the dynamic parameters of mobility management. Let the signaling cost for dynamic PNLAU be Cdy. When a paging request comes to an LA, it is put into the macro queue randomly with the probability p' and in the micro queue with the probability (1-p'). The value of p' is related to the paging load balance in the two queues [9].

So, for MMT_4, the cost denoted by T_4 is given by the following expression

$$T_4 = C_{pg}(1-p(Q)) + (M_a+1)/2)C_{pg} p(Q) + M_i' C_{dy} \quad (7)$$

where $C_{dy} = \mathbf{C}_{NLAU} + \mathbf{C}_{PLAU} + \mathbf{C'}_{INIT}$

$\mathbf{C'}_{INIT} = \gamma' (C_{pole} N_{cell} + C_{fail})$

C_{fail} is the cost of failure of call setup and wasted trunk, N_{cell} is the total number of cells, and C_{pole} is the polling cost.

$$C_{pg} = (m M_i W_{pi} / D'') (p' R_M + (1-p'))$$

D" is the no. of paging cycles within which an MT is found within the LA. R_M is a macro-micro ratio, important for load balance: m= (D"+1)/2.

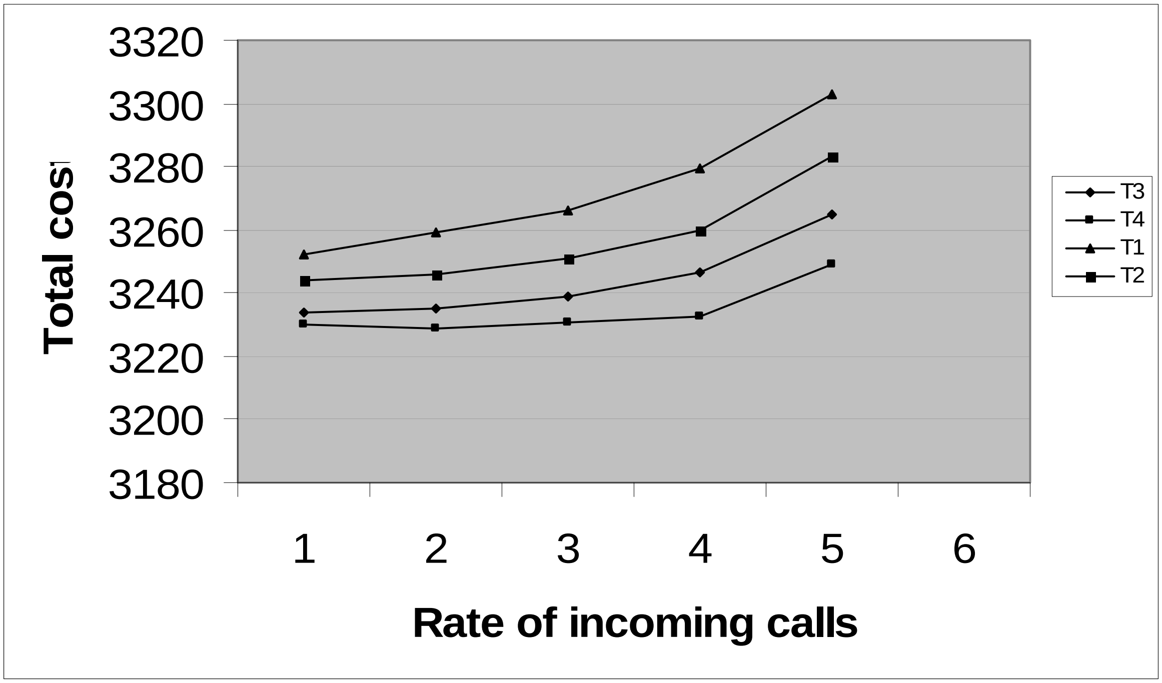

Figure 4. Signaling cost comparison for various MMTs.

5. Analysis of Delay

Using Little's law, the average delay D is given by:

$$D = q / \Lambda (1 - p(n))$$

where q is the average number of users in the system, p(n) is the probability of the queue being in such a state, where n paging messages are queued at that time, and Λ is the paging message arrival rate.

Delay for MMT_1 can be found from this equation as:

$$D_{T1} = q / \Lambda_{ma}(1 - p(n)) \quad (8)$$

where Λ_{ma} is the paging message arrival rate at macro cell tier.

The probability that the paged MT can be found in each micro-LA is $1/M_a$, where M_a is the number of micro-LAs overlapped with the macro-LA.

Let us define N to be the average number of times that a paging message will be broadcast in the micro-LAs until the paged user is found.

$$N= (M_a+1)/2$$

For MMT_2, the delay is

$$D_{T2} = D_{ma}(1-p_{ov}) + ((M_a+1)/2)D_{mi}\ p_{ov} \tag{9}$$

D_{ma} and D_{mi} are the delays in the macro and the micro cell tiers, respectively.

Let us define D_{T3} to be the average processing delay for MMT_3. Then

$$D_{T3} = D' (1 - E(N_{pnlau})) + ND'E(N_{pnlau}) \tag{10}$$

$E(N_{pnlau})$ denotes the average number of PNLAU events per check point event. The paging delay is lesser in MMT_4 because, unlike MMT_3, it is adaptive to HCNs.

Thus, because the LAU is done dynamically for every micro LA, less area has to be paged, and also the paging load balance takes less time.

Let us define D_{T4} to be the average processing delay for MMT_4. Then

$$D_{T4} = N\ D\ (T_a + T_i) \tag{11}$$

$$T_a = m/u + p\Lambda m(m+1) / 2u(u-p\Lambda m)$$

$$T_i = m/u + (1-p)\Lambda m(m+1) / 2u(u-(1-p)\Lambda m)$$

$1/u$ is the mean service time, and Λ is the call arrival rate such that $p\Lambda=\Lambda_{ma}$ and $(1-p)\Lambda=\Lambda_{mi}$.

6. Results and Discussion

The results are based upon some assumptions for important network parameters. For the purpose of simplification of analysis, LAs are taken to be circular with a radius of 600m. The vehicular MTs are supposed to have a homogeneous average velocity of 20m/sec. The time between two consecutive calls is taken to be much larger than average call holding time. The bandwidth in macro cell tier is taken to be as valuable as that in micro cell tier. The time interval between any two paging slots is normalized to be 1. The paging cost in a single cell is 463 units. Number of macro cells in a macro LA is taken to be 7 and each micro LA is supposed to have 7 micro cells if nothing else is mentioned.

For LAU purpose nnlau is taken to be r /100, the ratio Cnlau:Cplau:Cpage = 10:10:1, and ri/r =2/5%. Thus, the μma and μmi can be easily calculated. For simplicity of architecture it is also taken that the distribution of users is homogeneous throughout the LA. For SMMP, p is taken to be 0.5. Queue length is taken to be infinite. Call arrival rate is varied from 1 to 10 per unit time.

Figure 4 shows that, in comparison with the other techniques, MMT_4 performs better as the rate of incoming calls increases. While for MMT_2 the cost of signaling is not too high because it receives signal only from the macro cell tier, MMT_1 renders a much larger cost. The cost of MMT_4 is less than the other two techniques because the paging cost is small owing to the two tiered system and also optimal LAU guarantees less paging cost. MMT_4 renders about 0.84% less signaling cost than MMT_3 at point-5 of the graph.

For the delay factor, we find that the delay for MMT_1 is the least and that for MMT_3 is nearly as much as MMT_2. Delay of MMT_4 is a little less than that of MMT_3.

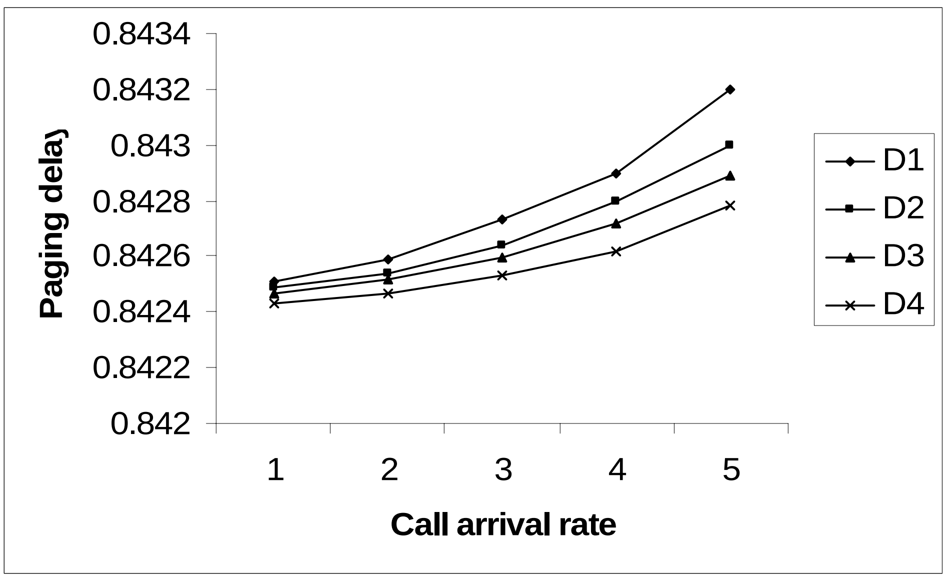

Figure 5. Paging delay comparison for MMTs

(Di correspond to D_{Ti}**)**

7. Conclusion

In conclusion, it can be said that MMT_4 is an overall good design for low cost MMT, with little delay, as it takes into consideration the dynamic nature of mobility management. Suitability to HCN and reduction in both cost and latency make it a better choice for mobility management in HCN than any other technique, specially when the base station covers larger area under one micro LA and the number of MTs is more than the number of pedestrian users. Even with real life scenario, where an MT may change place rapidly, as long as a relatively large micro LA is assigned to one base station, MMT_4 performs well.

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Appendix I

Step1a: Set the clock timers (ID Timer and Implicit Detach Timer), synchronized at with time T'. The value of T' is not fixed. (No. of PLAU messages per T' is not fixed).

Step1b: Set the probability that the next paging message would wait in the micro paging queue to be p.

Step2: Set the mobile configuration such that it receives signal from both the tiers.

Step2a: If the MT crosses micro LA boundary, send a NLAU message.

Step2b: Else, if it crosses micro cell boundary, no NLAU message is sent.

Step3: If ID Timer expires without any PLAU message within a certain T', CC records the MT to be detached from the next T'.

Step 3a: If a checkpoint event occurs, such as an incoming call, no new voice trunk is set up. The incoming call is dropped.

Step4: Else, the buffered LA information is replaced by the new PLAU information.

Step5: While T' does not expire.

Step5a: If new NLAU message arrives replace the existing registration information with the new one.

Step5a1: If checkpoint event, such as incoming call, occurs before new NLAU, initial voice trunk wasted.

Step5a2: Else, call is set up and monitored for handover.

Step5a3: The incoming paging request will wait in either of the two queues with a probability of p.

Step5a4: The paging message will be broadcasted in the entire partition area.

Step5b: If abnormal detachment occurs between previous PLAU and next checkpoint event, it will not be registered.

Step5c: If abnormal detachment occurs between two PLAU events with no new checkpoint event, it will be registered by the CC for the following PLAU.

Step6: If the latency between previous abnormal detachment and current checkpoint event is less than the latency between (a) previous PLAU and next NLAU (b) two PLAU messages (c) previous PLAU and current checkpoint, then next T' commences.

Appendix II

Each macro LA is taken to be made up of Ma macro cell and each micro LA is made up of Mi micro cells. For MMT_3, since a macro cell is also a micro LA, a macro LA overlaps with M_a micro LAs and covers Ma*Mi micro cells. (b)The arrival rate of paging messages for micro and macro cell tiers are taken to be Λ_{mi} and Λ_{ma}.. (c)The time that a mobile user will stay within the same micro LA is distributed with a mean of 1/μmi second.

Where, $\mu_{mi} = E[v]L/\Pi A$…………………(1)

Here, A and L are the area and perimeter of the micro LA. Also we have $\mu_{ma} = \mu_{mi} / \sqrt{M_a}$.

The cost for location update/paging process is defined as the paging cost for a paged mobile user to be found, plus the LAU cost on this mobile user since last time it is called. When LAU is operated in the macro cell tier (e.g., in MMT_1), define t_1 to be the time that a mobile user will stay in a micro-LA and t_2 to be the time interval between two consecutive calls to this mobile user. As assumed before, both t_1 and t_2 are exponentially distributed with mean $1/\mu_{mi}$ and $1/\mu_c$, respectively. Define $ft_1(t_1)$, $ft_2(t_2)$ to be the pdf functions for t_1, t_2 ; then:

$$f\,t_1(t_1) = \mu mi\, e^{-\mu mi}\, t1$$

$$f\,t_2(t_2) = \mu_c\, e^{-\mu c}\, t_2$$

An LAU is needed when t2 > t. Define p_u to be the probability that there is at least one LAU between any two consecutive calls to this mobile user. In

$p_u = p[t2 > t1] = \mu_{mi} /(\mu_{mi} + \mu_c)$………………(2)

The average number of location will be equal A_{T1}

$$A_{T1} = p_u / (1- p_u)^2$$