

# TECHNICAL RESEARCH REPORT

## Efficient Location Tracking of Mobile Nodes for Situation Awareness

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# EFFICIENT LOCATION TRACKING OF MOBILE NODES FOR SITUATIONAL AWARENESS \*

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## Abstract

*Mobile user tracking is the function of collecting, updating and maintaining information about the location of a mobile user based on situational awareness information. The tracking and connectivity information maintenance mechanism proposed by us is in the form of registration schemes which are of two types—single layer overlapping and multi-layer overlapping. Both types are static, simple to implement in a scenario such as that of a battlefield and under which overlapping registration areas of various sizes are allowed. The availability of various registration area sizes allow the mobile to pick the one that fits better to its message/mobility pattern. An algorithm is obtained which given an heterogeneous mobile population with a variety of message/mobility patterns and a registration scheme, determines an allocation of mobiles to registration areas such that the resulting aggregate registration and paging rates are below certain target values, whenever the target values are achievable.*

## INTRODUCTION

A major initiative to digitize the battlefield has been launched by the Army in order to take advantage of the rapid advancements in communication and computer systems. The commander of a digitized force has significant advantages over commanders of conventionally equipped forces, one of the most significant being an increased situational awareness. This requires harnessing the technology to help the commander and his forces better understand the situation that they are in so as to lead to improved decision making. This facet of the problem calls for efficient

mechanisms for gathering and dispersal of the situational data of the troops. In this paper we look at strategies which while being simple to implement in a scenario such as that of a battlefield are also highly efficient.

The scenario that we consider consists of a wireless network operating in a battlefield situation with a large number of mobile users (both vehicular and pedestrian). The situation can very well also be that corresponding to a natural disaster such as earthquakes or hurricanes which share similar characteristics with a battlefield. At any instant it may be necessary to have information about the location of any given mobile either to deliver the message to the mobile unit or for the purpose of decision making. This can be typically done by having a certain set of predesignated fixed or vehicular stations called base-stations page for the mobile until it is found. The set of base-stations which page the mobile may be decided by the paging strategy based upon the registration messages which the mobile sends to certain base-stations at regular intervals of time or space. The registration strategy is responsible for deciding when a mobile sends the registration messages and to which base-station. The area surrounding a given base-station such that a mobile present in the specified area corresponds with the given base-station is called a cell of the given base-station. Since we are mainly interested in efficient paging-registration strategies, in the sequel we assume that the base-stations and their positions and hence the cells are known a-priori.

A number of dynamic registration strategies for the commercial cellular environment have been proposed recently [2, 3, 4, 7]. Similar strategies could be considered for the scenario of interest here. For such a case it is known that the dynamic distance based strategy

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achieves significantly better trade-offs between paging and registration rates as compared to the different registration strategies proposed in the literature. But its implementation is not simple and more importantly it is computationally intensive from the point of view of the mobile. We also consider the registration strategy based on the concept of disjoint registration areas [5, 6]. The comparison between the different strategies is based on the registration rate  $g_r$ , which is the number of registration messages per cell boundary crossing and the paging rate  $g_p$ , which is the number of pagings per location request.

The following assumptions are made through out the paper. For the purpose of illustrating the performance of the proposed schemes the wireless system under consideration is assumed to be a cellular network represented by a regular hexagonal lattice. Also let  $X(t)$  denote the cell where the user resides at time  $t$ . The mobility profile of a user is represented by the *location process*  $X = \{X(t), t \geq 0\}$ . This is a piecewise constant process with state space the set of cells of the system. The state transitions correspond to crossings of cell boundaries. The location process is a homogeneous Markov chain. The probabilities of transition from a cell  $i$  to each one of its six neighbors is equal to  $1/6$ . The residence time in a cell is exponential with rate  $v$ , that is the average residence time in a cell is  $1/v$ . The rate  $v$  reflects the speed of the mobile. The position determination of the mobile may also be required either to deliver a message to it or for the purpose of decision making. Without loss of generality, we assume that the mobile is to be located so as to deliver a message to it. We assume that each mobile is receiving messages according to a Poisson process of rate  $\lambda$ . The message/mobility type of the mobile is characterized by the pair  $(\lambda, v)$ .

## THE OVERLAPPING REGISTRATION AREAS STRUCTURE

The type of registration/paging mechanism that we propose relies on a structure of group of cells called registration areas of the following type. A collection  $\mathcal{C} = \{S_i : i = 1, \dots, J\}$  of  $J$  subsets of cells (*registration areas*) is specified. This collection covers all cells in the system in the sense that every cell is included in at least one set of  $\mathcal{C}$ . The cells in each set  $S_i$  are contiguous or in other words no set  $S_i$  includes disjoint regions of cells. The sets  $S_i$  might be arbitrarily overlapping otherwise. In the rest of the paper we will consider registration areas that consist of a collection

of cells in a regular hexagonal arrangement. The *size*  $d$  of such a registration area will be taken to be the number of cells in one side of the hexagon minus one.

Each mobile is associated (*registered*) with exactly one registration area at each time  $t$ . This area always contains the cell where the mobile currently resides. As soon as the mobile enters a cell that does not belong to the registration area the mobile was most recently registered to, it needs to be registered again to any one of the registration areas which the new cell belongs to. The registration rate  $g_r$ , in number of registration messages per cell boundary crossings, depends on the registration scheme and is a measure of its performance. In certain cases we will need to refer to the registration rate expressed in registration messages per time unit that is  $v^{-1}g_r$ .

The mobile is paged whenever there is a message directed to it. The paging rate  $g_p$ , in paging messages per time unit, depends both on the rate with which a mobile is receiving messages and on the paging mechanism. If the mobile is paged in all cells of its registration area  $S_i$  at the time the call is placed, then the number of paging messages generated is equal to  $|S_i|$ , the number of cells in  $S_i$ . If  $p_i$  is the steady state probability that the mobile is registered in area  $S_i$  and assuming Poisson call generation process, the paging rate in pagings per location request is

$$g_p = \sum_{i=1}^M p_i |S_i|. \quad (1)$$

If all the registration areas are of equal size  $|S|$ , then the paging rate becomes  $g_p = |S|$ . The paging rate in paging messages per time unit is  $\lambda g_p$ . Several methods which try to reduce the paging rate are under investigation currently [1, 8]. If any of these methods is employed, the paging rate is less than that in equation (1). In this paper, it is assumed that a mobile is paged simultaneously in all cells where it may reside.

## SINGLE LAYER OVERLAPPING REGISTRATION AREAS

In a single layer registration system, all the registration areas have the same size. A single layer system is specified by the common size of the registration areas and their locations. In our performance study we will consider two additional single layer systems. One in which each registration area overlaps with three others and another where each registration area overlaps with six others. The first single layer system

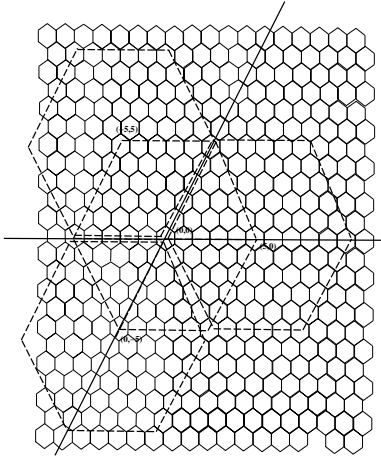


Figure 1: *3-overlapping single layer registration system for the hexagonal cellular lattice*

will be referred to as the 3-overlapping system and is shown in figure 1 with registration areas of size  $d=5$ . The second single layer system will be referred to as the 6-overlapping system.

The performance of the system is characterized by the pair  $(g_p, g_r)$  of registration and paging rates respectively. In a single layer system the paging rate is a function of the size of the registration areas only and not of the relative locations of the areas or the registration scheme. If the size of the area is  $d$ , then the paging rate is  $g_p = 1 + 3d(d + 1)$ .

Next, we need to come up with an expression for the registration rate also. Hence, let  $\{t_i^r\}_{i=1}^\infty$  be the collection of all times at which the mobile registers itself. In stationary operation the registration rate  $\hat{g}_r$ , in registration messages per time unit, is

$$\frac{1}{E[t_{i+1}^r - t_i^r]},$$

that is the inverse of the expected time between two successive crossings of the registration area boundary. Normalizing by the average cell residence time, the registration rate in registration messages per cell crossings is

$$g_r = \frac{v}{E[t_{i+1}^r - t_i^r]}, \quad (2)$$

Lets denote by  $E_c$  the set of possible *entry* cells of the registration area, that is those cells which might be visited first when the user enters the registration area. In the case of disjoint registration areas,  $E_c$  contains all cells in the boundary of the registration region. In the case of one registration area centered

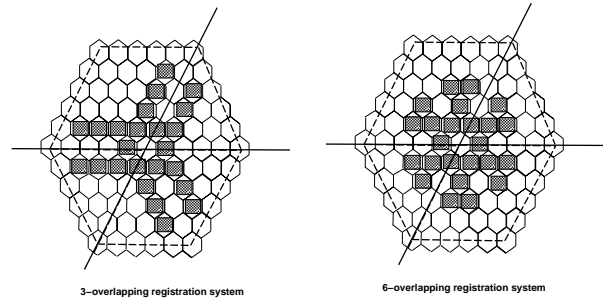


Figure 2: *Possible entry cells for the 3- and 6-overlapping registration system*

in each cell,  $E_c$  contains only the center cell of each registration area. The sets  $E_c$  for the 3-overlapping and 6-overlapping systems are illustrated in figure 2. Let  $p_e(i)$  be the probability that a mobile will enter the registration area in cell  $i$  and  $T(i)$  be the expected number of cell crossings until the mobile moves out of the registration area, from the time it starts in cell  $i$ . Then the registration rate can be expressed as

$$g_r = \frac{1}{\sum_{i \in E_c} p_e(i) T(i)}. \quad (3)$$

It is fairly intuitive (and can be easily shown) that the closer a cell  $i$  is to the center of the registration area, the higher  $T(i)$  will be and in fact  $T(i)$  is maximum when  $i$  is the center cell. Hence the registration rate will be smaller for registration schemes that result in sets of possible starting cells concentrated more around the center cell.

In figure 3 we see plots of the pair  $(g_p, g_r)$ . Curves corresponding to different single layer systems are depicted. The points of each curve are obtained for different registration area sizes ranging from 1 to 10. As expected the strategy with one registration area per cell has the best performance. Note also that the 6-overlap system as well as the 3-overlap system have performance curves very close to that of the one registration area per cell system. This is achieved while each cell belongs to 2 or 3 registration areas respectively, and independently of the size of the registration areas compared to  $1 + 3d(d + 1)$  registration areas containing each cell for the latter strategy.

The loading of the system in terms of registration and paging messages per time unit  $\hat{g}_p$  and  $\hat{g}_r$  respectively depends on the mobility of the mobile. They are

$$\hat{g}_p = \lambda g_p \quad \text{and} \quad \hat{g}_r = v^{-1} g_r$$

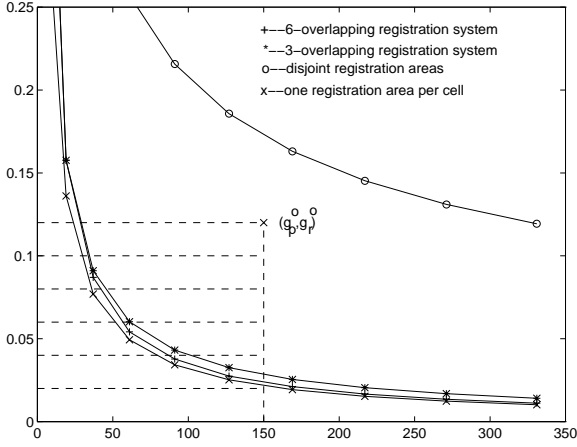


Figure 3: The normalized (mobility independent) registration/paging rate pair curves for different registration strategies, and registration area sizes varying from 1 to 10

The performance curves can be normalized by the parameters  $\lambda$  and  $v$  each time to get the performance curve for a specific mobility type. Given the available capacities, or equivalently desirable paging and registration rates  $(g_p^o, g_r^o)$  in the downlink and uplink channels respectively, and the performance curves for the specific mobility type, we can determine which single layer strategies and corresponding registration area sizes are feasible under these requirements. For example, the strategies with performance points within the shaded rectangle, achieve paging and registration rates less than  $(g_p^o, g_r^o)$  respectively. Note that with disjoint registration areas the pair  $(g_p^o, g_r^o)$  is not achievable.

In general we have a mix of mobiles with  $N$  possible message mobility types characterized by the pairs  $(\lambda_n, v_n)$ ,  $n = 1, \dots, N$ . Assume that  $M_n$  mobiles have the mobility pattern  $(\lambda_n, v_n)$ . If there is a single layer of registration areas with normalized paging registration rate pair  $(g_p, g_r)$ , then the corresponding rates per time unit will be

$$\hat{g}_r = \sum_{n=1}^N v_n^{-1} M_n g_r \quad , \quad \hat{g}_p = \sum_{n=1}^N \lambda_n M_n g_p.$$

In case of a traffic mix as above, a combination of registration areas may improve performance significantly.

### MULTILAYER OVERLAPPING REGISTRATION AREAS

Consider a multilayer registration scheme consisting of a number of overlaid single layer registration areas as the ones discussed in the previous section. For simplicity and without loss of generality assume that all layers are of the same type and they differ by the size of the registration areas. Assume that there are  $K$  layers with registration area sizes  $d_k$ ,  $k = 1, \dots, K$  indexed in increasing order, that is  $d_{k+1} > d_k$ ,  $k = 1, \dots, K - 1$ .

In a multilayer system, each mobile has the option to choose the registration areas layer that it will use to update its location registration. In general,  $f_{nk}$  mobiles of type  $n$  may select to use layer  $k$  for registrations. The aggregate paging and registration rates in this case are

$$\hat{g}_r = \sum_{k=1}^K \sum_{n=1}^N v_n^{-1} f_{nk} g_r^k \quad , \quad \hat{g}_p = \sum_{k=1}^K \sum_{n=1}^N \lambda_n f_{nk} g_p^k.$$

The question of feasibility of a pair  $(g_p^o, g_r^o)$  of paging and registration rates can be placed as follows. Identify an allocation of mobiles to layers  $f_{nk}$ ,  $n = 1, \dots, N$ ,  $k = 1, \dots, K$  such that

$$\begin{aligned} \sum_{k=1}^K \sum_{n=1}^N v_n^{-1} f_{nk} g_r^k &\leq g_r^o \\ \sum_{k=1}^K \sum_{n=1}^N \lambda_n f_{nk} g_p^k &\leq g_p^o \end{aligned}$$

In the following we characterize the region of achievable paging-registration rates pair when the mix of mobile types and the multilayer system is specified. This is done by an algorithm which constructs the boundary of the region of achievable rate pairs.

Consider allocations where all mobiles of the same type are assigned to the same layer. These allocations are specified by a vector  $l = (l_n, n = 1, \dots, N)$  where  $l_n$  is the layer to which all mobiles of type  $n$  are allocated to.

Consider the sequence of allocations  $l^i$ ,  $i = 1, \dots, N(K - 1)$  where  $l_n^1 = 1$   $n = 1, \dots, N$  and  $l^{i+1}$  is obtained from  $l^i$  as follows

For each type  $n$  such that  $l_n^i < K$  compute the ratio

$$\frac{v_n^{-1} (g_r^{l_n^i} - g_r^{l_n^i+1})}{\lambda_n (g_p^{l_n^i+1} - g_p^{l_n^i})}. \quad (4)$$

Select the type  $n_o$  such that  $l_{n_o}^i < K$  and for which the ratio given by (4) is maximum. Let  $l_{n_o}^{i+1} = l_{n_o}^i + 1$

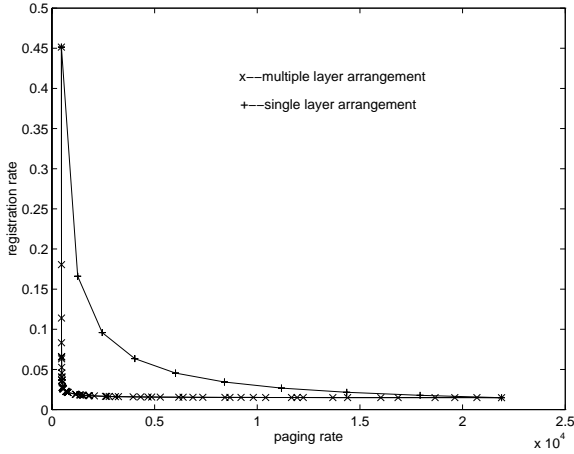


Figure 4: Performance of the multilayer and single layer strategies for the 3-overlapping arrangement

and  $l_n^{i+1} = l_n^i$ ,  $n \neq n_o$ . Consider the piecewise linear curve that is defined by the sequence of the performance points of the sequence of allocations  $l^i$ ,  $i = 1, \dots, N(K-1)$ . This curve is the lower boundary of the region of rate pairs which are feasible in the sense of satisfying the inequalities for some appropriate allocation  $f_{nk}$ . An extensive related study and a rigorous treatment of the properties of the algorithm is available in [9].

Comparative evaluation of the performance of the single layer and the multiple layer strategies are shown in figure 4. For the multi-layer strategy we assume 10 layers having different registration area sizes ranging from 1 to 10. 8 different types of mobiles with different pairs of  $(\lambda_n, v_n)$  are assumed. Only one mobile is assumed to be in each type. The curve on the top represents the performance when all mobiles are assigned to the same layer, while the curve in the bottom is the lower boundary of the region of achievable rates. From repeated simulations it has been found that, the wider the disparities between the different types, the wider the performance gap becomes between the single layer and the multilayer case.

## CONCLUSION

The registration scheme proposed here is static and simple to implement and can achieve performance identical with the distance based dynamic strategy or very close to that with minimal additional overhead as compared to the static strategy with disjoint registration areas. The other feature of the registration scheme is that it provides flexibility for adaptation to the mobility profile of the user, by allowing the user to

choose among registration areas of various sizes. An important further topic of research that remains and which is particularly important in the context of a battlefield because of the presence of mobile basestations is about the determination of base-stations. In this work it was assumed predetermined since our emphasis was to come up with efficient location tracking schemes, the basis of comparison being the registration and paging rates achievable.<sup>1</sup>

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