User Modelling and Performance Evaluation of Distributed Location Management for Personal Communications Services

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Personal Mobility has to be supported by efficient location management. Several strategies for tracking user locations have been proposed. The efficiency of these strategies very much depends on user behaviour. We present a user model which takes into account the mobility of a user as well as the traffic matrix of incoming calls. The mobility model does not only take into account the call-to-mobility ratio, but also the geographic distribution of user mobility. The traffic matrices of incoming calls are modelled depending on the current location and on the home location of the users involved in a call.

A simple methodology is given which helps to evaluate different location management strategies in terms of signalling load, processing load in an Intelligent Network environment, query load to a distributed database and mean response times depending on different parameters of the user model. Finally, a case study is given which compares a GSM-like tracking strategy to a strategy which is based on a hierarchically distributed database.

1. INTRODUCTION

Location Management for Personal Communications Services has to be able to locate a subscriber, e.g. when there is an incoming call. To this end, some data about the current location of a user is usually kept in the network. In GSM, for example, a user registers to a visitor location register (VLR) at his current location, which is informed whenever the user changes location areas. Within location areas users are paged when necessary. Each user is assigned to a home location register (HLR) which stores at which VLRs its subscribers are currently registered and which provides the VLRs with data about the users which is needed locally, e.g. for authentication. This solution with its two-level hierarchy has often been criticized, especially in the case when subscribers roam far away from their Home Location Register. Every time such a subscriber changes VLRs or receives calls, which probably often originate close to his current location, signalling to the distant HLR is required. Based on different assumptions about user behaviour, several proposals for improvement have been made. [10] cites a proposal (which has some similarity with a proposals in [21]) where a user is searched first at local VLRs before the distant HLR is queried. In [9] a local anchor scheme is proposed to minimize location update signalling to a distant HLR. In [13], [14] chains of forwarding pointers are suggested for subscribers who change location more frequently than they receive calls. Whereas in [15] a caching strategy is presented for subscribers who change location less frequently.

With the expected large number of subscribers and increase of location update rates – due to smaller cells and multi-network-operator environments – the GSM solution might not be adequate. The two-level hierarchy does not scale very well. Several proposals [1], [2], [6], [7], [8], [26], [29], [30] have been made which use multi-level hierarchical distributed databases together with sophisticated data distribution and data retrieval techniques. Some proposals try to reduce network impact by adapting certain parameters to individual user behaviour (e.g.: [8], [15], [25]). Similar ideas for location management of distributed objects in the Internet have been presented in [27]. All these proposals usually reduce signalling cost in exchange for increased processing cost and overall database size. On the contrary, in [17] and in [4] signalling is assumed to be cheap and signalling cost is increased in exchange for simpler protocols and reduction of database loads. In [17], e.g., VLRs are abolished and only HLRs exist.

The performance of different location management strategies and network architectures heavily depends on user behaviour. An important figure in describing user behaviour is the call-to-mobility ratio (*CMR*) [13], [15], [22], [23]. However, it is not sufficient. The traffic relations between users and the geographic expansion of movement have also to be taken into account. They might even be decisive. In [7], [18], [19], [20], and [24] this is considered to some extent. In [19] and [24] provision of personal communications services across several networks is examined.

A comparatively simple user model is needed in order to understand the pros and cons of different location management strategies better and to support network design. The goal of optimal network design, including database location, is to deploy network topologies that minimize total network cost while selecting locations, allocating capacity, and routeing traffic to accommodate demand and performance requirements [31].

2. LOCATION MANAGEMENT PROCEDURES

Updating location information (location update) and finding the current location of a user (find operation) are the two most important location management procedures. Closely related – and therefore also considered here – are the user authentication procedure during a location update and the call setup procedure. In this article we focus on signalling and database transactions that affect the network beyond the current location of a user. Procedures that can be performed by using data available at the current location of a user are not taken into consideration here. Examples of those procedures are ciphering, allocation of temporary identifiers, attach/detach procedures, periodic location updates within one location area, and user authentication at call setup. Handover procedures are not discussed either.

Location information has to be updated when a user leaves a (possibly user-specific [8], [25]) area where he can be found by the network and moves to another location where he wants to be reached. In GSM, a location update is performed via the air interface without encryption. In order to protect user identity, a temporary identifier is used to identify the user. The entity in the network which allocated the temporary identifier is usually able to provide the actual identity of the user. Before a location update can be accepted, authentication has to be performed. This is done by sending an input challenge (RAND) to the subscriber whose SIM card (or similar device) computes a signed result (SRES) using a cryptographic algorithm and a secret key. Service logic needs to have access to RAND/SRES pairs, which are provided by an authentication centre. Usually, a vector with several pairs is produced. Each pair is only used once and the vector with the unused pairs is kept close to the current location of a user. During a location update, user data, including the authentication vector, is transferred from the previous location of the subscriber to his current location. After successful authentication, location information within the network is updated, an action which includes deletion of user data at the previous location.

Call setup to a subscriber can be requested from any location area. In order to enable routeing of the call to the called party, two different approaches exist: (a) Invocation of a find operation before call setup which provides sufficient routeing information (e.g. to some extend in GSM), and (b) influencing routeing during call setup (e.g. in [29]), which means that the find operation and call setup are performed simultaneously.

We have investigated how location management can be realized in an Intelligent Network environment [11], [12]. We present two possible realizations. The first realization is derived from the GSM mobility management procedures, we call this the *GSM-like realization*. The second realization adopts* an approach presented by J. Z. Wang [29], where a distributed database with a tree-structure is proposed. A subscriber who is located in a location area beneath his home database node is registered only there. If a subscriber is located in a location area which is not beneath his home database node, a chain of pointers leads along the nodes of the database tree to the current location. When a subscriber moves from one database node to another, the pointer chain has to be rearranged, which usually only requires limited signalling. Figure 1 shows the database hierarchy and an example of a chain of pointers from the home database node to the current location of a user. We call this the *Wang-like realization*. The according information flows for the two realizations in an Intelligent Network environment include authentication, resolution of temporary identifiers, location updates, and incoming calls.

3. THE USER MODEL

The procedures *location update* and *incoming call* are usually triggered by user behaviour. In order to be able to evaluate the performance of different location management strategies, it is important to know how often and between which net-

* Instead of influencing routeing during call setup, we invoke a find operation first

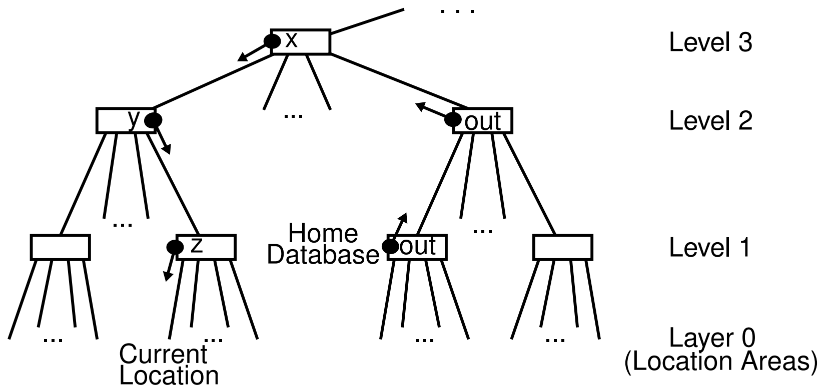

Figure 1. Database hierarchy and example of a chain of pointers according to [29]

work entities these procedures take place. The user model presented here focuses on these aspects. It is composed of two parts: a mobility model and a call model. The mobility model is independent of the call model. The destination of calls depends on the mobility behaviour of the involved parties. The call-to-mobility ratio (*CMR*) defines the ratio between incoming calls and location updates. The user model usually represents different classes of customers. In each class the overall behaviour can be regarded as the superposition of the behaviour of all members of the class. Thus, the model does not necessarily have to represent the detailed behaviour of an individual customer.

3.1. The Mobility Model

From the network point of view, the relevant aspects of user location can be expressed in terms of location areas. At a given geographic location, a user can be registered to a (possibly user-specific) location area. We define several classes of users*. For each class there exists a home location area. The mobility of the users of a specific class c is defined by a simple Markov chain, which is also used in [5].

A state probability $\pi_i^{(c)}$ is assigned to each registration state, with:

$$\sum_i \pi_i^{(c)} = 1 \tag{1}$$

When leaving state i a transition to state j takes place with probability $p_{ij}^{(c)}$, where:

$$\sum_{j,\, j \neq i} p_{ij}^{(c)} = 1 \tag{2}$$

The mean sojourn times $1/\mu_i^{(c)}$ within the different states can be obtained from the equilibrium equations under steady state condition:

$$\pi_i^{(c)} \cdot \mu_i^{(c)} = \sum_{j,\, j \neq i} \pi_j^{(c)} \cdot \mu_j^{(c)} \cdot p_{ji}^{(c)} \tag{3}$$

* Different classes represent different user behaviour. Users with similar behaviour but with different home location areas are in different classes.

and from the definition of the mean location update rate:

$$\bar{\mu}^{(c)} = \sum_i \pi_i^{(c)} \cdot \mu_i^{(c)} \tag{4}$$

The location update rate between state *i* and state *j* is then given by:

$$\lambda_{ij}^{(c)} = \mu_i^{(c)} \cdot p_{ij}^{(c)} \tag{5}$$

For the sake of simplicity, we assume that the sojourn times within the states are negative-exponentially distributed (M). In [19] a Semi-Markov process with general independent (GI) sojourn time distributions is used for the same purpose.

The mobility model of class *c* customers is essentially determined by the $\pi_i^{(c)}$, the $p_{ij}^{(c)}$ and $\bar{\mu}^{(c)}$. The $\pi_i^{(c)}$ may be dependent on the geographic distance from the home location [7] and the $p_{ij}^{(c)}$ reflect neighbourhood between the states.

Each customer class consists of $N^{(c)}$ customers. The mean number of customers in location area *i* (S_i) can be obtained by the superposition of the mobility behaviour of all customers:

$$S_i = \sum_c N^{(c)} \cdot \pi_i^{(c)} \tag{6}$$

3.2. The Call Model

For the call activity of a user class, the call-to-mobility ratio $CMR^{(c)}$ and the geographic distances which are defined between the registration states are of importance. The according traffic matrix can be defined dependent on these geographic distances. We identify four types of calls*:

- *Type 1* calls from parties whose home location is "close" to the home location of the called party.
- *Type 2* calls from parties whose current location is "close" to the current location of the called party
- *Type 3* calls from parties whose current location is "close" to the home location of the called party.
- *Type 4* calls from parties whose home location is "close" to the current location of the called party.

In a simple approach we define discrete distances between location areas (*dist{i,j}*). For each type of call *t* we also define the probability Π_{Call} *(t,d)* which only depends on the distance *d*, so that for each *t* the sum of Π_{Call} over all possible distances equals unity:

$$\sum_d \Pi_{Call}^{(c)}(t, d) = 1 \tag{7}$$

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* "close" means that the call rate is dependent on the geographic distance.

If for each type of call we define a probability of occurrence w_t (with $\Sigma w_t = 1$), we can calculate the call setup rates between LA i and LA j from:

$$\gamma_{ij}^{(c)} = CMR^{(c)} \cdot \bar{\mu}^{(c)} \cdot \sum_{t=1}^{4} w_t^{(c)} \cdot \pi_j^{(c)} \cdot r_{t,i,j}^{(c)} \tag{8}$$

where $r_{t,i,j}$ is defined individually for each type of call:

$$r_{1,i,j}^{(c)} = \sum_d \Pi_{Call}^{(c)}(1,d) \cdot \sum_{k \mid dist\{h_k, h_c\} = d} \frac{N^{(k)} \cdot \pi_i^{(k)}}{\sum_{l \mid dist\{h_l, h_c\} = d} N^{(l)}} \tag{9}$$

$$r_{2,i,j}^{(c)} = \Pi_{Call}^{(c)}(2, dist\{i,j\}) \cdot \frac{S_i}{\sum_{k \mid dist\{k,j\} = dist\{i,j\}} S_k} \tag{10}$$

$$r_{3,i,j}^{(c)} = \Pi_{Call}^{(c)}(3, dist\{i,h_c\}) \cdot \frac{S_i}{\sum_{k \mid dist\{k,h_c\} = dist\{i,h_c\}} S_k} \tag{11}$$

$$r_{4,i,j}^{(c)} = \sum_d \Pi_{Call}^{(c)}(4,d) \cdot \sum_{k \mid dist\{h_k, j\} = d} \frac{N^{(k)} \cdot \pi_i^{(k)}}{\sum_{l \mid dist\{h_l, j\} = d} N^{(l)}} \tag{12}$$

where h_c is the home location area of a class c customer.

3.3. The Mobility Model in Large Networks

A mobility model in the general form presented above is difficult to handle numerically for a network with a large number of location areas. In order to reduce the state space, we arrange the different states at the leaves of a symmetrical tree structure with H levels. We define the distance between two states as the number of hops to reach the first common predecessor in the tree. One of the states is supposed to be the home state. The state probabilities depend only on the distance from the home state. We assume that all states which have the same distance d from the home state belong to the same class d. All states within one class have the same state probability. The probability of a class c customer to be in the class d states is denominated $\Pi_d^{(c)}$ (with $\sum_d \Pi_d^{(c)} = 1$). The transition rate between two states only depends on their distance in the tree and their state probabilities. We define the probability of a transition from a class d state to states in the distance l of a class c customer as $P_{d,l}^{(c)}$, with $\sum_l P_{d,l}^{(c)} = 1$. Since states in the same distance d from a state may have different state probabilities, the transition probabilities are weighted according to the state probabilities. Finally we get:

$$\pi_i^{(c)} = \frac{\Pi_{dist\{h_c, i\}}^{(c)}}{\sum_{k \mid dist\{h_c, k\} = dist\{h_c, i\}} 1} \tag{13}$$

$$p^{(c)}_{i,j} = \frac{P^{(c)}_{\mathrm{dist}\{h_c,\, i\},\, \mathrm{dist}\{i,\, j\}} \cdot \pi^{(c)}_j}{\sum\limits_{k \,|\, \mathrm{dist}\{i,\, k\} = \mathrm{dist}\{i,\, j\}} \pi^{(c)}_k} \tag{14}$$

With these assumptions the state space can be reduced dramatically. In each state class we choose one representative state and reduce all states within this class that have the same distance from the representative state to a single state. The state probabilities and the transition probabilities are simply aggregated. In a symmetrical tree structure with H levels the state space is reduced to $H \cdot (H + 1)/2$ (or fewer) states. The system of linear equations according to (3) and (4) is reduced to $H \cdot (H + 1)/2$ (or fewer) equations. Figure 2 shows an example.

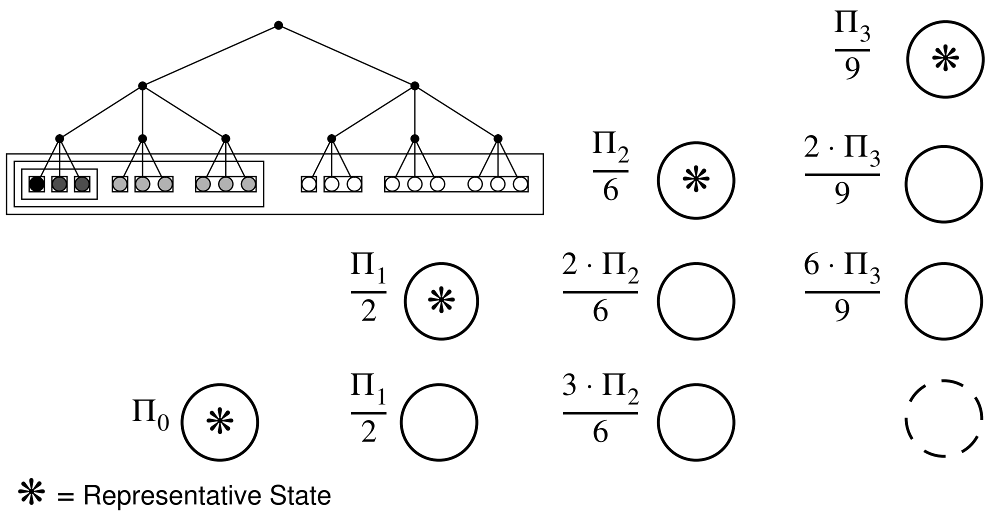

Figure 2. Reduced state space with 9 states for a tree with *4* levels and *18* leaves

4. THE NETWORK MODEL

The network model only models functionality in the control plane. Important entities are:

- the signalling network (signalling links and signalling points),
- the Intelligent Network infrastructure, and
- the nodes of the distributed database.

In the following we present a very simple network model which is designed to only give a rough estimate of the network behaviour. We have already published a more detailed model and methodology which could also be applied [3],[16].

Signalling links are modelled as infinite servers, with deterministic delay, depending on their length. All other network entities are analysed using a very simple approximation. They are modelled as $\Sigma M_i/M_i/1$ servers. Overall network mean response times are obtained by simply adding mean sojourn times of the different entities. In each node a set of servers (processors) handles signalling messages (in

SS#7: MTP and SCCP functionality), whereas another set of processors handles IN requests (TCAP, INAP processes, and functional entity actions). Databases are regarded as separate entities with several processors that handle requests. Figure 3 shows the model for one node in the network. Different mean processing times (h_i) can be assigned to different messages and to different functional entity actions (FEAs).

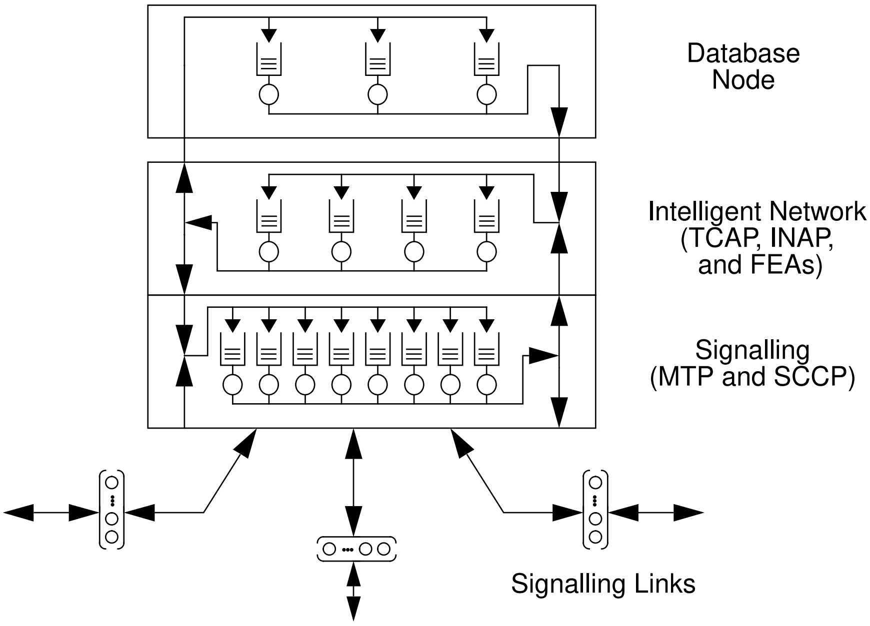

Figure 3. Model of a network node

A simple flow analysis together with a queueing network analysis, which is based on a decomposition approximation as described above, is performed and yields mean numbers of database entries per database node, mean database access rates per node and per scenario, mean signalling load, mean load on IN physical entities, and, finally, mean end-to-end response times for different location management procedures.

5. A CASE STUDY

5.1. The Studied System

We study a network with *64* location areas. In the GSM-like realization *16* nodes, which combine HLR and VLR functionality, serve these location areas. It is assumed that the node which serves the home location area of a user also acts as the user's HLR. In the Wang-like realization a hierarchical tree structure with three levels is assumed, where one node at level 3 serves *4* nodes at level *2*, which serve *16* nodes at level *1*. Signalling in both cases follows the tree structure. We assume that the distance between a level *l* node and a level *l+1* node is four times larger than the distance between a *l-1* node and a level *l* node. We consider similar user behaviour, i.e. we have *64* user classes which differ only with respect to their home location area. Thus, we obtain a completely symmetric network load.

The tree structure which determines the user behaviour is assumed to be identical to the tree structure of the distributed database and the signalling network. For all user classes and all types of calls, we assume $CMR = 1$ and $\Pi_{Call}(0) : \Pi_{Call}(1) : \Pi_{Call}(2) : \Pi_{Call}(3) = 1 : 1 : 1 : 1$. Because we want to study the dependence of the performance of the different location management strategies on the geographic distribution of user location, we define five types of mobility. The rate of location updates is kept constant, whereas the geographic distribution and the distance of location updates is varied. We define a quantity which we call *mobility coefficient*. It is the ratio between the mean distance of a user from his home location area to the mean distance of all location areas from the user‘s home location area. Table 1 shows the parameters of the five types of mobility.

Table 1: Parameters and mobility coefficient of the different types of user mobility

Mobility type	$\Pi_0 : \Pi_1 : \Pi_2 : \Pi_3$	$P_1 : P_2 : P_3$ [a]	Mobility coefficient
1[b]	*1 : 0 : 0 : 0*	*1 : 0 : 0*	*0*
2	*8 : 4 : 2 : 1*	*64 : 8 : 1*	*0,2745*
3	*1 : 1 : 1 : 1*	*16 : 4 : 1*	*0,5614*
4	*1 : 2 : 4 : 8*	*4 : 2 : 1*	*0,8483*
5	*1 : 3 : 12 : 48*	*1 : 1 : 1*	*1,0*

[a] according to section 3.3: $P_{d,l} = P_l$ for all d.

[b] Type 1 is a limiting case, which has to be treated slightly differently.

In addition to the varying mobility behaviour, the effect of the different call types is studied as well. In each case we assume that only one type of call determines the behaviour of all users.

We dimension network resources so that the offered load to a single network entity equals 0.8 Erlang in the worst case. For processing times, we make the following assumptions:

Table 2: Processing times

Processing time of an incoming signalling message	*5 ms*
Processing time of an outgoing signalling message	*5 ms*
Processing time of a transfer signalling message	*10 ms*
Sum of TCAP and INAP processing times	*5 ms*
Database read operation	*5 ms*
Database write operation	*5 ms*
Signalling link delay between the different levels is *1ms*, *4ms* and *16 ms* respectively.	

5.2. Results

Table 3 shows the mean number of database entries per user for the different mobility types and for the two studied realizations.

Table 3: Mean number of database entries per user

Mobility type	Wang-like realization	GSM-like realization
1	*1*	*1*
2	*1.533*	*1.2*
3	*2.5*	*1.5*
4	*3.667*	*1.8*
5	*4.375*	*1.938*

Figure 4 shows the probability distribution (PD) of the aggregated distances of the signalling relations for the find operation for different types of calls and mobility type 5.

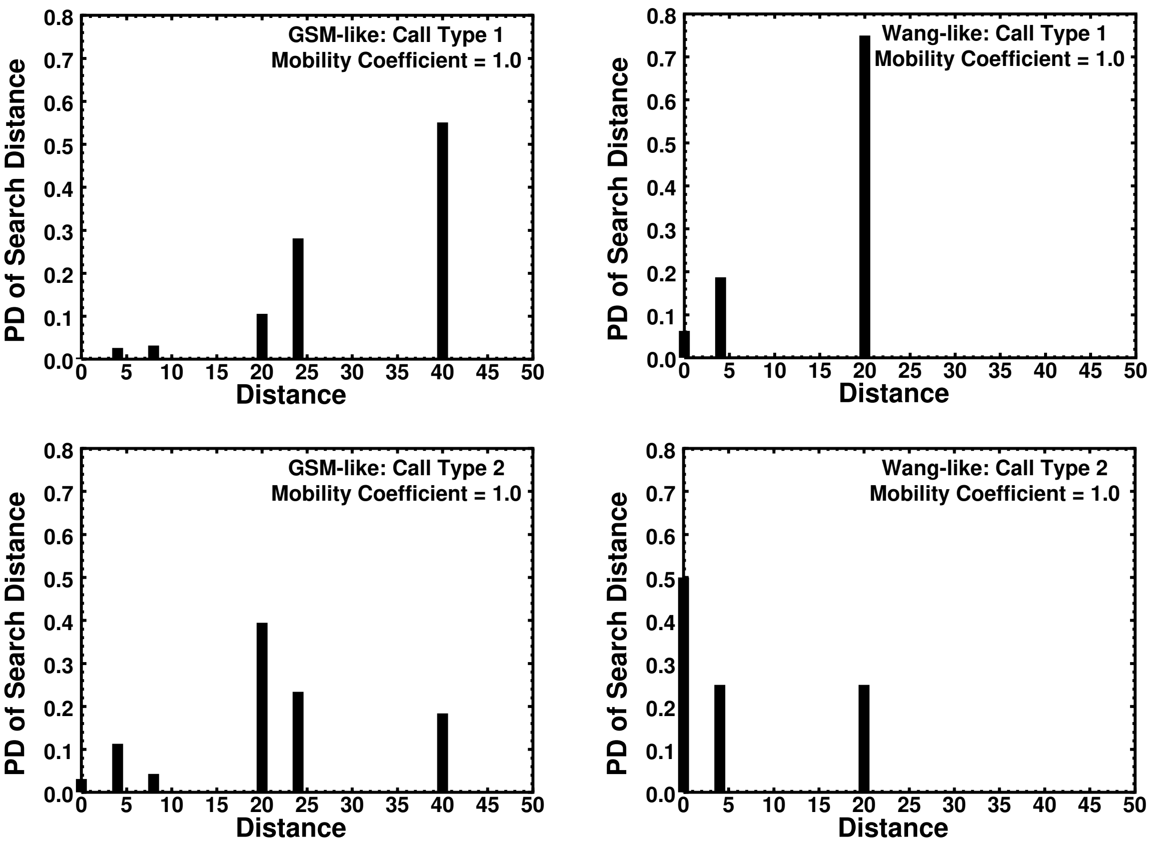

Figure 4. Probability distributions of the search distance of the find operation for call types 1 and 2 with mobility coefficient *1.0* in the GSM-like realization (l.h.s.) and in the Wang-like realization (r.h.s.)

Figure 5 shows the mean response times of location updates (LU) and of find operations for systems with different mobility types and different call types. The mean LU update delays in the systems with different call types are similar. With increased mobility coefficient, the GSM-like realization has longer response times. The mean search delays depend very much on the call types. In the Wang-like system with type 2 calls, the mean search delay is almost insensitive to the mobility coefficient. For the other types however, the mean search delays are comparable to the mean search delays in the GSM-like realization with type 2 and type 3 calls. The GSM-like realization performs worst for type 1 and type 4 calls.

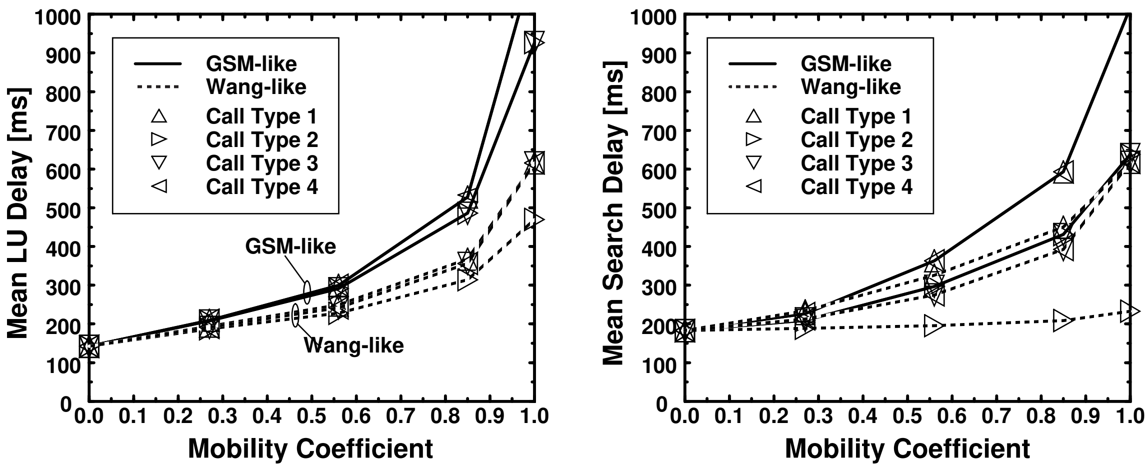

Figure 5. Mean location update delay and mean search delay for systems with different mobility types and different call types

6. CONCLUSIONS

A detailed user model has been presented which enables to compare different location management strategies within different network architectures and under varying user behaviour. Besides important capacity figures, also performance figures are obtained by using a simple network model and an approximating decomposition technique. An extensive case study gives an idea of the results which can be obtained by using this methodology.

First results show that a distributed database does not necessarily reduce the mean search delay. This is especially true for type 3 calls. It can be shown that in a multi-network operator environment a location management strategy based on a distributed database is not able to exploit locality of calls and movement except for the case when a common location management database is implemented which is used by all networks. Further studies have to decide the question whether GSM-like location management fulfils the requirement of third generation mobile and personal communications systems (as proposed in [28]), or whether a more sophisticated approach based on distributed databases is needed.

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