Location Management of Correlated Mobile Users in the UMTS

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Abstract—In this paper, we propose concurrently searching for correlated mobile users in mobile communications networks. Previous work either focuses on locating a single mobile user or assumes that the locations of mobile users are statistically independent. We first propose a mobility model in which the movements of mobile users are statistically correlated. Next, we use the theory of Markov chain to derive the joint probability density function of the locations of mobile users. In addition, we propose a novel approach to discover the correlations among the locations of mobile users without explicitly calculating the joint probability density function. Our simulation results indicate that exploring the correlations among the locations of mobile users could significantly reduce the average paging delay and increase the maximum stable throughput.

Index Terms—Mobility management, paging, statistical correlation, UMTS.

1 Introduction

Mobile communications networks have been evolved from the second generation (e.g., GSM) to the 2.5 generation (e.g., General Packet Radio Service or GPRS), and then to the third generation (e.g., Universal Mobile Telecommunications System or UMTS). However, as pointed out in [43], the concept of mobility management has remained the same. Typically, a mobility management scheme constitutes of a location update scheme and a paging scheme [1]. The cells in a UMTS service area are partitioned into a number of groups. To deliver services to a mobile station, the cells in the group covering the mobile station will page the mobile station to establish the radio link. The UMTS contains the circuit-switch domain and the packet-switch domain. In the circuit-switch domain, a location area is composed of a number of cells. Base stations belonging to a location area are controlled by a single Vistor Location Register (VLR). Similarly, in the packet-switch domain, a routing area consists of a number of cells. A routing area is typically a subset of a location area. Base stations in a routing area are controlled by a single SGSN (Serving GPRS Support Node). More details about the mobility management in the UMTS could be found in [42], [44].

In the last decade, many location update schemes were proposed. Basically, these schemes were movement-based [2], [3], timer-based [4], distance-based [5], [6], profile-based [7], state-based [8], or velocity-based [9]. Schemes that use a hybrid of the above strategies were also proposed [10], [11]. It was proven in [12], [13] that distance-based schemes achieve better performance compared to movement-based schemes and timer-based schemes. Some proposed schemes [14], [15] suggested that a mobile should register its location only when it enters some predefined cells, referred to as reporting centers. Liang and Haas [16] proposed a predictive distance-based user-tracking scheme based on the Markov-Gaussian random process. Bhattacharya and Das [17] proposed a novel information-theoretic approach for location update.

A location area is composed of a number of cells. Some researchers assumed that a mobile user sends a location update message to the system whenever it enters a new location area and concentrated on the design of an optimal location area. Kim and Lee [18] proposed an integer-programming model to find the optimal location area, which may take on an irregular shape. Abutaleb and Li [19] claimed that the problem of finding the optimal location area, when the size of the location area is constrained, is NP-hard. Other researchers assumed that location areas are given and focused on the decision problem of whether a mobile user should send a location update message when it enters a new location area. Das and Sen [20] proposed a genetic algorithm to decide whether a mobile should update its location when it enters a new location area.

Recently, Li et al. [21] formulated the problem of minimizing the costs of location update and paging in the movement-based location update scheme as a convex optimization problem. Saraydar et al. [22] proposed a continuous formulation for the problem of one-dimensional location area design to overcome the computational difficulty associated with the original combinatorial formulation. Jeon and Jeong [23] proposed an improved probabilistic location update scheme. Yeun and Wong [24] applied probabilistic paging to contention-free mobility management. Akyildiz and Wang [25] proposed a dynamic location management scheme based on intersystem location update and intersystem paging for multitier PCS (Personal Communications Services) networks. Escalle et al. [26] proposed the three-location area location-tracking algorithm. Ma and Fang [27] proposed a two-level pointer forwarding strategy. Casares-Giner and Mataix-Oltra [28]

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proposed a hysteresis-type location update scheme. Wu et al. [29] proposed an analytical framework for mobility management in PCS networks. In addition, they proposed the probabilistic selective paging scheme. Cayirci and Akyildiz [30] proposed the user mobility pattern scheme for location update and paging. Li et al. [31] analyzed the movement-based location update scheme. Araujo and Boisson de Marca [32] compared several strategies for reducing paging and location update costs. A survey on location management schemes could be found in [33].

Lyberopoulos et al. [34] proposed paging the cell that a mobile registered with most recently and then page all other cells in the location area, if necessary. Akyildiz and Ho [6] proposed the shortest-distance-first paging scheme. Rose and Yates [35] proved that given the probabilistic information about the position of a mobile, to minimize the average paging cost, the cells with the higher probabilities must be paged before the cells with the lower probabilities are paged. Wang et al. [36] described three types of methods to obtain the probabilistic information about the locations of mobile users: geographical computation, empirical data, and mathematical models. Krishnamachari et al. [37] proposed an efficient algorithm to solve the problem of minimizing the average paging cost under the worst-case paging delay constraint. Abutaleb and Li [38] showed that the problem of minimizing the average paging cost under the mean paging delay constraint can be solved in $O(2^n)$ time. Gau et al. [39] proved that the optimal sequential paging problem in the cellular networks is mathematically equivalent to the multicast flow control problem in the Internet. Rezaiifar and Makowski [40] proposed a paging scheme based on the theory of optimal search.

Gau and Haas [41] proposed the concurrent search approach that could simultaneously locate $k \geq 2$ mobile users within k time slots even when there is only one logical paging channel. They assumed that the locations of mobile users are statistically independent. However, there are cases in which the locations of mobile users are inherently statistically correlated. For example, passengers in a car are always in the same cell irrespective of the mobility pattern of the car. In addition, family members and friends tend to spend a significant amount of time together. In this paper, we propose exploring the correlations among the locations of mobile users to further reduce the average paging delay as well as increase the maximum stable throughput. Our proposed scheme is compatible with location update schemes with static location areas.

The rest of the paper is organized as follows: In Section 2, given the joint probability density function of the locations of mobile users, we formulate an integer-programming problem to maximize the expected number of located mobile users in a time slot. In Section 3, we propose a mobility model that captures the correlations among the locations of mobile users. In addition, we derive the joint probability density function for the mobility model. In Section 4, we propose a new scheme for locating correlated mobile users without explicitly deriving the joint probability density function or solving the integer-programming problem. In Section 5, we show the simulation results that justify the usage of the proposed scheme. Discussions are included in Section 6. Our conclusions are included in Section 7. Related proofs can be found in the Appendix which can be found on the Computer Society Digital Library at http://computer.org/tmc/archives.htm.

2 Problem Formulation

Suppose there are N_c cells and M mobile users in the Universal Mobile Telecommunication System (UMTS), which is a third-generation cellular network. Denote the index of the ith cell in the UMTS by c_i, $\forall i \in \{1, 2, 3, .., N_c\}$. The time axis is divided into slots of identical lengths. Let Z_n^i be the index of the cell in which mobile user i resides at time slot n. It is assumed that for each fixed value of i, $Z_1^i, Z_2^i, Z_3^i, \ldots$ constitute a stationary stochastic process. Since the stochastic process $\{Z_n^i\}_{n=1}^{\infty}$ is stationary regardless of the value of i, for each value of $i \in \{1, 2, 3, .., M\}$, there exists a random variable L_i such that

$$P\{L_i = c_j\} = \lim_{n \to \infty} P\{Z_n^i = c_j\}, \forall j \in \{1, 2, 3, .., N_c\}. \quad (1)$$

Let N_p be the total number of logical paging channels in a base station (BS). A logical paging channel could be a frequency band, a mini time slot, or an orthogonal CDMA (Code Division Multiple Access) code. Let θ be a stationary paging policy. A stationary paging policy consists of $N_c \times N_p \times M$ binary variables. In particular, $\forall i \in \{1, 2, 3, .., N_c\}$, $j \in \{1, 2, 3, .., N_p\}$, $k \in \{1, 2, 3, .., M\}$, $\theta(i, j, k) = 1$ if BS i uses the jth logical paging channel to page mobile user k, and $\theta(i, j, k) = 0$, otherwise. Each paging policy has to satisfy the following conditions: First, as assumed in [41], a paging channel could be used to page at most one mobile user in one time slot. Thus,

$$\sum_{k=1}^{M} \theta(i, j, k) \leq 1, \forall i \in \{1, 2, 3, .., N_c\}, j \in \{1, 2, 3, .., N_p\}. \quad (2)$$

Second, a base station pages a particular mobile station at most once in a time slot. Therefore,

$$\sum_{j=1}^{N_p} \theta(i, j, k) \leq 1, \forall i \in \{1, 2, 3, .., N_c\}, k \in \{1, 2, 3, .., M\}. \quad (3)$$

Under the above conditions, we look for an optimal stationary paging policy θ that maximizes the expected number of located mobile users in a time slot, which is denoted by R and is defined as follows:

$$R = \sum_{(x_1, x_2, .., x_M) \in S^M} \Bigg[P\{L_1 = x_1, L_2 = x_2, .., L_M = x_M\} \cdot \sum_{k=1}^{M} \sum_{j=1}^{N_p} \theta(x_k, j, k) \Bigg], \quad (4)$$

where $S = \{c_1, c_2, c_3, .., c_{N_c}\}$ and $S^M = S \times S \times .. \times S$.

Then, the problem of concurrent search of correlated mobile users could be formulated as maximizing the value of R subject to the constraints in (2) and (3). The problem is an integer-programming problem. Since there are $N_c \cdot N_p \cdot M$ binary variables in the above integer-programming problem, the brutal-force approach could solve the problem in $O(2^{N_c \cdot N_p \cdot M})$ time.

3 The Basic Mobility Model

In this section, we propose a mobility model for correlated mobile users in the UMTS. Without loss of essential generality, it is assumed that the UMTS is composed of square cells and there are $N_c = w^2$ cells in the network. In addition, a cell in the network is indexed by (x, y), where $x, y \in \{1, 2, 3, .., w\}$. Let $\Omega = \{(x, y) | x, y \in \{1, 2, 3, .., w\}\}$. Let $N((x, y))$ be the set of indexes of cells that are adjacent to the cell indexed by (x, y). In addition, let $|N((x, y))|$ be the cardinality of the set $N((x, y))$. In a network composed of square cells, $|N((x, y))| \in \{1, 2, 3, 4\}$, $\forall (x, y) \in \Omega$.

The M mobile users in the network are partitioned into α clusters such that the movements of mobile users in two clusters are statistically independent. When the movements of any two mobile users are statistically independent, as assumed in [41], every mobile user forms a cluster and $\alpha = M$. On the other hand, when the movements of any two mobile users are statistically correlated, $\alpha = 1$ and there is only one cluster of mobile users in the network. Let β_i be the total number of mobile users in the ith cluster, $\forall i \in \{1, 2, 3, .., \alpha\}$. To provide a concrete example of correlated mobile users, it is assumed that there exists a unique cluster head in each cluster. The assumption will be dropped later in the paper. We further explain the concept of cluster head as follows: When a cluster is composed of passengers in a car, the driver is seen as the cluster head, since the driver decides the moving direction. When a cluster consists of members of a family, one of the parents could be the cluster head. The above statement is true especially when all the children are very young. It is based on the observation that young children usually follow their parents. For illustration purposes, it is assumed that a cluster contains only two mobile users. Namely, $\beta_i = 2$, $\forall i \in \{1, 2, 3, .., \alpha\}$. The model can be easily extended to the general case in which $\beta_i > 2$.

We propose using three sequences of random variables to model the movements of mobile users in a cluster. Consider an arbitrary cluster. Let $i = h(j)$ be the index of the cluster head and j be the index of the other mobile user in the cluster. Denote the location of mobile user k at time slot n by $Z_n^k = (X_n^k, Y_n^k)$, $\forall n \geq 1$. For each k and n, $X_n^k, Y_n^k \in \{1, 2, 3, .., w\}$. We assume that the location process $\{Z_n^i\}_{n=1}^{\infty}$ of the cluster head is Markovian. When the DTMC (Discrete-Time Markov Chain) $\{Z_n^i\}_{n=1}^{\infty}$ is a random-walk process, the corresponding transition probability function is derived as follows: Let q be an arbitrary real number in $(0, 1)$. It is assumed that at the end of time slot n, the cluster head moves from (x_n, y_n) to each of the adjacent cells with probability $\frac{1-q}{|N((x_n, y_n))|}$. In addition, with probability q, the cluster head stays in the current cell at the end of a time slot. The value of q corresponds to the speed of the cluster head. When the value of q is very close to 1, the cluster head seldom moves. On the other hand, when the value of q is approximately 0, the cluster head rarely stays in a cell for two consecutive time slots.

The transition probability function of $\{Z_n^i\}_{n=1}^{\infty}$ is shown as follows:

$$P\{Z_{n+1}^i = (x_{n+1}, y_{n+1}) | Z_n^i = (x_n, y_n)\} = \begin{cases} q, & \text{if } (x_{n+1}, y_{n+1}) = (x_n, y_n) \\ \frac{1-q}{|N((x_n, y_n))|}, & \text{if } (x_{n+1}, y_{n+1}) \in N((x_n, y_n)) \\ 0, & \text{otherwise.} \end{cases}$$

To model the correlation between the movements of mobile users, we adopt α sequences of i.i.d. (independent, identically distributed) random variables

$$\{W_n^1\}_{n=1}^{\infty}, \{W_n^2\}_{n=1}^{\infty}, .., \{W_n^{\alpha}\}_{n=1}^{\infty}$$

with a common state space $\{0, 1\}$ and a common probability density function. The random variable W_n^k is used for the kth cluster at time slot n. Since the movements of mobile users in distinct clusters are statistically independent, $W_{n_1}^{k_1}$ and $W_{n_2}^{k_2}$ are statistically independent, $\forall k_1 \neq k_2, n_1, n_2 \geq 1$. Let $r = P\{W_n^k = 1\}$, $\forall n, k$. Then, $r \in [0, 1]$. When it is clear from the context, we abbreviate W_n^k by W_n.

Next, we introduce the mobility model for mobile user j, which is not a cluster head. Recall that $h(j)$ is the index of the cluster head associated with mobile user j. Without loss of essential generality, it is assumed that $Z_1^j = Z_1^{h(j)}$. Namely, the initial location of a mobile user is identical to that of the corresponding cluster head. Let $\widehat{d_n}$ be a random vector that represents the direction of moving of the cluster head at the end of time slot n. More precisely, $\widehat{d_n} = Z_{n+1}^{h(j)} - Z_n^{h(j)}$. In a network composed of square cells, $\widehat{d_n} \in \{(0, 0), (0, 1), (0, -1), (1, 0), (-1, 0)\}$, $\forall n \geq 1$. Let d_n be a random vector that represents the direction of moving of mobile user j at the end of time slot n. Namely, $d_n = Z_{n+1}^j - Z_n^j$. Similarly,

$$d_n \in \{(0, 0), (0, 1), (0, -1), (1, 0), (-1, 0)\}, \forall n \geq 1.$$

We assume that the value of Z_{n+1}^j depends only on the values of Z_n^j, $Z_n^{h(j)}$, $Z_{n+1}^{h(j)}$, and W_n as follows: When $W_n = 1$, d_n, and $\widehat{d_n}$ are statistically correlated such that

$$d_n = \begin{cases} \widehat{d_n}, & \text{if } Z_n^j + \widehat{d_n} \in \Omega \\ (0, 0), & \text{otherwise.} \end{cases}$$

On the other hand, when $W_n = 0$, d_n, and $\widehat{d_n}$ are independent random variables. Furthermore,

$$P\{d_n = \delta\} = \begin{cases} q, & \text{if } \delta = (0, 0) \\ \frac{1-q}{|N(Z_n^j)|}, & \text{if } Z_n^j + \delta \in N(Z_n^j) \\ 0, & \text{otherwise.} \end{cases}$$

When $r = 1$, $W_n = 1$, $\forall n \geq 1$. In this case, in each time slot, the movement of mobile user j is identical to that of the corresponding cluster head. When $r = 0$, the movements of mobile user j are always statistically independent of the movements of the associated cluster head. Therefore, the parameter r represents the correlation between the movements of two mobile users. When the mobile user j is not a cluster head, the value of Z_{n+1}^j depends not only on the value of Z_n^j, but also on the values of $Z_n^{h(j)}$ and $Z_{n+1}^{h(j)}$. Therefore, in general, the stochastic process $\{Z_n^j\}_{n=1}^{\infty}$ is not a discrete-time Markov chain. However, the stochastic process $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$ is a discrete-time Markov chain.

Theorem 1. *The stochastic process* $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$ *is a discrete-time Markov chain.*

Proof. See the Appendix which can be found on the Computer Society Digital Library at http://computer.org/tmc/archives.htm. □

The derivation of the transition matrix for the discrete-time Markov chain $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$ is quite straightforward and is omitted due to the limit of space.

We now prove that there exists a steady-state probability distribution for the DTMC (Discrete-Time Markov Chain) $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$. Let S be the state space of the DTMC. Then, $|S| \leq N_c \times N_c < \infty$ and, therefore, the state space is finite. We will prove the existence of the steady-state probability distribution by showing that the DTMC $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$ is aperiodic, irreducible, and positive-recurrent. We first prove that the DTMC is aperiodic and irreducible.

Lemma 1. *The DTMC* $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$ *is aperiodic.*

Proof. See the Appendix which can be found on the Computer Society Digital Library at http://computer.org/tmc/archives.htm. □

Lemma 2. *The DTMC* $\{Z_n^{h(j)}\}_{n=1}^{\infty}$ *is irreducible.*

Proof. See the Appendix which can be found on the Computer Society Digital Library at http://computer.org/tmc/archives.htm. □

Lemma 3. *The DTMC* $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$ *is irreducible.*

Proof. See the Appendix which can be found on the Computer Society Digital Library at http://computer.org/tmc/archives.htm. □

Based on the above lemmas, it can be shown that there exists a steady-state probability distribution for the DTMC $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$.

Theorem 2. *There exists a steady-state probability distribution for the DTMC* $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$.

Proof. See the Appendix which can be found on the Computer Society Digital Library at http://computer.org/tmc/archives.htm. □

The steady-state probability distribution for the DTMC $\{(Z_n^j, Z_n^{h(j)})\}_{n=1}^{\infty}$ can be derived by solving a set of stationary equations. Let s_i be the *i*th state in S and $\pi_i = \lim_{n\to\infty} P\{(Z_n^j, Z_n^{h(j)}) = s_i\}$ be the steady-state probability that the system is in the state s_i. Let T be the transition probability function such that

$$T(a,b) = P\{(Z_{n+1}^j, Z_{n+1}^{h(j)}) = s_b | (Z_n^j, Z_n^{h(j)}) = s_a\}.$$

Then,

$$\pi_b = \sum_{a=1}^{|S|} \pi_a \cdot T(a,b), \forall b \in \{1,2,3,..,|S|\}. \tag{5}$$

In addition,

$$\sum_{a=1}^{|S|} \pi_a = 1. \tag{6}$$

With the above two sets of equations, the stationary probabilities, π_as, where $a \in \{1,2,3,..,|S|\}$, could be derived.

We have derived the probability distribution function for the locations of mobile users in a cluster. Since mobile users in distinct clusters are statistically independent, the joint probability distribution function for the locations of all mobile users in the UMTS is equivalent to the product of the probability distribution functions over all clusters.

For the convenience of the readers, we summarize the proposed mobility model as follows: First, mobile users are partitioned into clusters and the movements of mobile users in distinct clusters are statistically independent. Second, the movements of correlated users in a cluster are based on the following assumptions:

Assumption 1. *The location process* $\{Z_n^{h(j)}\}_{n=1}^{\infty}$ *of the cluster head is Markovian.*

Assumption 2. *The stochastic process* $\{W_n\}_{n=1}^{\infty}$ *consists of i.i.d. random variables.*

Assumption 3. *The location* Z_{n+1}^j *of mobile user* j *that is not a cluster head depends only on* $Z_n^j, Z_n^{h(j)}, Z_{n+1}^{h(j)}, W_n$ *and is related by the* d_n *process.*

4 A Novel Algorithm

In this section, we propose a novel algorithm to locate correlated mobile users without explicitly deriving the joint probability density function for the locations of mobile users. A drawback of the integer-programming approach proposed earlier in the paper is that the computational complexity is too high. With the new scheme, it is no longer necessary to solve the integer-programming problem or derive the joint probability density function. In addition, it should be emphasized that the scheme does not require the system to identify the cluster head of a cluster.

Without loss of essential generality, it is assumed that all base stations in the UMTS are controlled by a control center. In practice, the UMTS contains the circuit-switch domain and the packet-switch domain. In the circuit-switch domain, a location area is composed of a number of cells. Base stations belonging to a location area are controlled by a single Visitor Location Register. Similarly, in the packet-switch domain, a routing area consists of a number of cells. Base stations in a routing area are controlled by a single SGSN from the viewpoint of the Internet. Therefore, our scheme could be used in a location area or a routing area.

We first define some terms that will be used in the proposed scheme. There are two lists in the control center. The unlocated mobile user list includes the indexes of unlocated mobile users and is denoted by Θ. The urgent list, denoted by U, contains the indexes of unlocated mobile users with calls that have waited for at least D_{max} time units, where D_{max} is an arbitrary positive real number. In addition to the two lists, there are N_c queues in the control center, where N_c is the total number of cells in the network. The *j*th queue in the control center is denoted by Q_j,

$\forall j \in \{1, 2, 3, .., N_c\}$. Let t be the index of a time slot. Denote the total number of packets in Q_j at time slot t by $q_j(t)$. When a new call arrives, the control center first identifies the corresponding mobile user. Let the index of the mobile user be i. For each queue Q_j, the control center creates a new packet, denoted by $PK_j(i)$. Next, the packet $PK_j(i)$ will be inserted into Q_j to indicate that the base station in the *j*th cell has not yet paged mobile user i. The priority of $PK_j(i)$ is denoted by $PR_j(i)$. A larger value of $PR_j(i)$ corresponds to a lower priority.

To calculate the priority of a packet, we introduce the concepts of displacement and effective sample. First, let $D_{t_1,t_2}(i,j)$ be the displacement between the location of mobile user i at time slot t_1 and the location of mobile user j at time slot t_2. Let W_r be an arbitrary natural number and $(x_i(t), y_i(t))$ be the coordinates of the cell in which mobile user i resides at time slot t. If mobile user i is located at time slot t_1, mobile user j is located at time slot t_2, and $|t_1 - t_2| < W_r$, $D_{t_1,t_2}(i,j) = |x_i(t_1) - x_j(t_2)| + |y_i(t_1) - y_j(t_2)|$. Otherwise, $D_{t_1,t_2}(i,j)$ is defined to be infinity. The definition of $D_{t_1,t_2}(i,j)$ reflects that only the recent locations of a mobile user could be used to predict the current location of the correlated mobile user. Second, let $S_t(i,j)$ be the total number of effective samples for mobile user i and mobile user j from time slot $t - W_r$ to time slot $t-1$. The value of $S_t(i,j)$ represents the total number of pairs of time instances from time slot $t - W_r$ to time slot $t-1$ when both mobile user i and mobile user j are located. In particular,

$$S_t(i,j) = \sum_{k_1=1}^{W_r} \sum_{k_2=1}^{W_r} I(D_{t-k_1,t-k_2}(i,j) < \infty), \tag{7}$$

where $I(condition)$ is the indicator function with value one if the condition is true and with value zero if the condition is false.

To calculate the average displacement between two mobile users, we first define the accumulated displacement between mobile user i and mobile user j at time slot t as follows:

$$V_t(i,j) = \sum_{k_1=1}^{W_r} \sum_{k_2=1}^{W_r} D_{t-k_1,t-k_2}(i,j) \cdot I(D_{t-k_1,t-k_2}(i,j) < \infty). \tag{8}$$

Next, the average displacement is equivalent to the value of the accumulated displacement divided by the total number of effective samples. Let $\phi_t(i)$ be the index of the mobile user with the highest correlation to mobile user i at time slot t from the viewpoint of the control center. Since correlated mobile users tend to remain close as the system evolves, mobile user $\phi_t(i)$ should be the mobile user with the minimum average displacement to mobile user i. Therefore,

$$\phi_t(i) = \arg\min \frac{\sum_{u=1}^{t} V_u(i,j)}{\sum_{u=1}^{t} S_u(i,j)}, \tag{9}$$

where the minimum is taken over the set

$$\{j : j \in \{1, 2, 3, .., M\}, j \neq i\}.$$

In the above equation, to make the formula concise, it is understood that if $\sum_{u=1}^{t} S_u(i,j) = 0$, then

$$\frac{\sum_{u=1}^{t} V_u(i,j)}{\sum_{u=1}^{t} S_u(i,j)} = \infty.$$

When there are ties, the random tie-breaking rule is used.

Let $R(i)$ be the last known location of mobile user i in terms of cell index. Let $\Gamma_t(i)$ be the last located time of mobile user i from the time origin to the beginning of time slot t. Denote the coordinates of the *i*th cell by (x_i, y_i). Let $d(i,j) = |x_i - x_j| + |y_i - y_j|$ be the distance between the *i*th cell and the *j*th cell. Let $\lambda_1 \geq 0$, $\lambda_2 \geq 0$, and $\kappa \geq 0$ be three arbitrary real numbers. The priority of $PK_j(i)$ depends on the values of $d(j, R(i))$ and $d(j, R(\phi_t(i)))$. In particular, at time slot t,

$$\begin{aligned} PR_j(i) = {} & \lambda_1 \cdot e^{\kappa \cdot (t - \Gamma_t(i))} \cdot d(j, R(i)) \\ & + \lambda_2 \cdot e^{\kappa \cdot (t - \Gamma_t(\phi_t(i)))} \cdot d(j, R(\phi_t(i))). \end{aligned} \tag{10}$$

The role of $PR_j(i)$ is further explained as follows: Since the total number of available paging channels in a cell is limited, a number of calls compete for the paging channels in a cell and a base station has to make a decision on the assignment of the paging channels. In the proposed scheme, each base station makes its own decision independently and the decision is based on two factors. The first factor is the distance from the base station to the last known location of the mobile user corresponding to a competing call. The second factor is the distance between the base station and the last known location of the mobile user with the highest correlation to the mobile user associated with a competing call. The exponential terms before the distance terms are used to reflect that the closer the last located time to the current time is, the more accurate the last known location as a prediction for the current location is.

The complete algorithm for locating correlated mobile users is shown as follows:

Step 0: Initially, all N_c queues in the control center are empty. Set $t = 0$. Choose $\kappa \geq 0$, $\lambda_1 \geq 0$, and $\lambda_2 \geq 0$. The unlocated mobile user list Θ is empty. The Urgent mobile user list U is also empty.

Step 1: Let Y_{t-1} be the number of calls that arrive during the time interval $[t-1, t)$. For each of these Y_{t-1} calls, sequentially do the following and then go to Step 2.

1. Let i be the index of the corresponding mobile user. Add the index i to the list Θ.
2. For each queue j, where $j \in \{1, 2, 3, .., N_c\}$, create $PK_j(i)$. Set

$$\begin{aligned} PR_j(i) = {} & \lambda_1 \cdot e^{\kappa \cdot (t - \Gamma_t(i))} \cdot d(j, R(i)) + \lambda_2 \cdot e^{\kappa \cdot (t - \Gamma_t(\phi_t(i)))} \\ & \cdot d(j, R(\phi_t(i))) \end{aligned}$$

and put $PK_j(i)$ into queue j.

Step 2: Update the urgent list U (and the unlocated mobile user list Θ). Select and remove the first $\min\{N_p, |U|\}$ indexes from the urgent list U and then command all base stations to simultaneously page the mobile users with the selected indexes. Let $N'_p = N_p - \min\{N_p, |U|\}$. For each value of j, where $j \in \{1, 2, 3, .., N_c\}$, do the following.

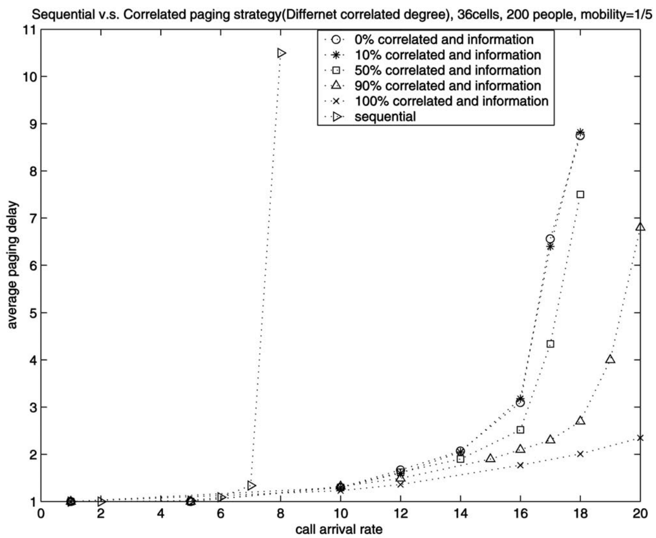

Fig. 1. The impact of correlation.

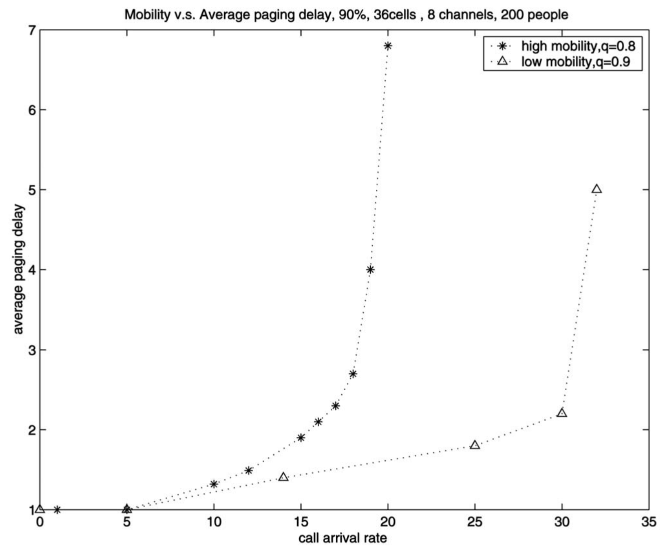

Fig. 2. The impact of mobility.

1. Select and remove $s(j) = \min\{N'_p, q_j(t)\}$ packets with the highest priorities from the jth queue, where $q_j(t)$ is the total number of packets in queue j at time slot t.
2. Let $f(j,1), f(j,2), .., f(j, s(j))$ be the integers such that $PK_j(f(j,1)), PK_j(f(j,2)), .., PK_j(f(j,s(j)))$ are the above selected packets. Command base station j to page mobile users $f(j,1), f(j,2), .., f(j,s(j))$.

Step 3: Wait for responses from all the base stations till the end of the current time slot.

Step 4: For each mobile user μ that is located in the current time slot, do the following:

1. For each value of j, where $1 \leq j \leq N_c$, if $PK_j(\mu) \in Q_j$, remove $PK_j(\mu)$ from Q_j.
2. Remove μ from the unlocated mobile user list Θ.
3. Update the last known location of mobile user μ.

Step 5: Increase the value of t by one and then go to Step 1.

We now elaborate on the Step 4 of the above algorithm. Recall that the packet $PK_j(i)$ resides in Q_j at the control center implies that base station j has not paged mobile user i yet. At any time instance, for each queue at the control center, there is at most one packet corresponding to a specific mobile user. Once mobile user μ is located by a base station, it is no longer necessary for other base stations to page the mobile user. To avoid base stations unnecessarily page mobile user μ in the future, all packets associated with mobile user μ must be removed from the control center.

5 Simulation Results

In this section, we use simulations to evaluate the proposed approach. Our simulation results indicate that exploring the correlations among the locations of mobile users could increase the maximum stable throughput of the UMTS and decrease the average paging delay.

5.1 Simulation Method

The network contains $N_c = w^2$ cells, which are indexed by (x, y), where $1 \leq x, y \leq w$. In each cell, there are N_p paging channels. In addition, there are a total of M mobile users roaming inside the network. The mobile users move according to the cluster-based mobility model introduced earlier in the paper.

Let λ be the average call arrival rate. Let B_i be the total number of calls that arrive in time slot i, $\forall i \geq 0$. It is assumed that $B_0, B_1, B_2, \ldots$ are i.i.d. random variables and for each $i \geq 0$, B_i is a Poisson-distributed random variable with mean equal to λ. Whenever a new call arrives, the system randomly selects a mobile user to be the callee. In the proposed heuristic algorithm, the value of κ is set to zero. In addition, unless explicitly stated, $\lambda_1 = 3$ and $\lambda_2 = 1$.

5.2 Simulation Results

We first study the performance of the proposed algorithm when $N_c = 36$, $N_p = 8$, and $M = 200$. In addition, the value of D_{max} is set to be 10. In Fig. 1, we show the advantages of exploring the correlations among the locations of mobile users. When the traditional sequential paging scheme is used, the maximum stable throughput is no greater than 8, which is the value of N_p. The maximum stable throughput is the maximum call arrival rate under the constraint that the average paging delay is finite. When the correlation coefficient r is equivalent to 50 percent and the proposed concurrent search algorithm is used, the maximum stable throughput is greater than 16, which represents a 100 percent increase. As the value of r increases, the maximum stable throughput increases as well. When the value of r is 0.9 and the proposed concurrent search algorithm is used, the maximum stable throughput is larger than 20. It is also observed that when the correlation coefficient is zero, the proposed algorithm outperforms the sequential paging scheme. The performance improvement is due to that the system could concurrently search for a number of mobile users. In Fig. 2, we show the impact of mobility on the average paging delay. In the higher mobility case, $q = 0.8$ and in the lower mobility case, $q = 0.9$. Given a fixed call arrival rate, when the mobility of mobile users increases, the average paging delay increases. As the mobility increases, the last known location of a mobile user becomes a less accurate prediction for the current location of the mobile user. As a result, the probability of locating a mobile user within D_{max} time units decreases.

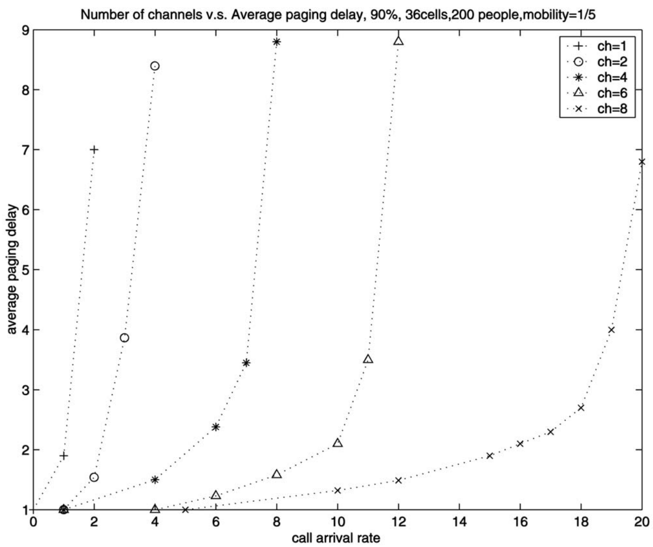

Fig. 3. The impact of total number of paging channels.

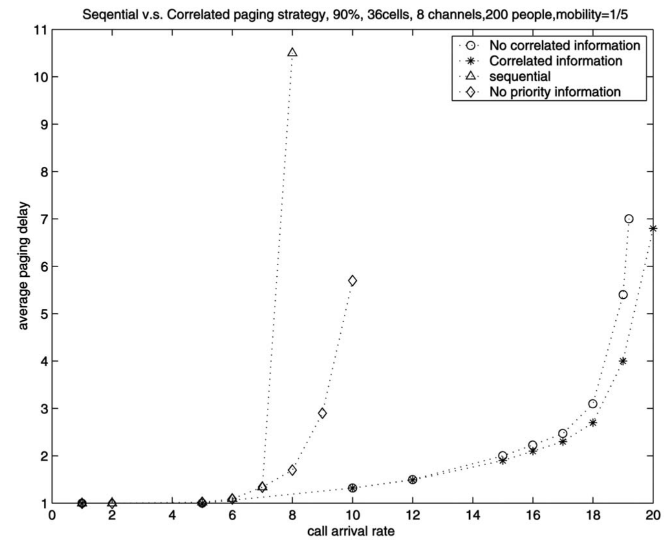

Fig. 4. Advantages of using the correlation.

In Fig. 3, we show the impact of the total number of paging channels on the maximum stable throughput. When $N_p = 1$, the maximum stable throughput is about 2. When the value of N_p increases to 4, the maximum stable throughput is close to 8. When there are eight paging channels in a cell, the maximum stable throughput is larger than 20. In Table 1, we list the 95 percent confidence intervals [45] for the average paging delays in Fig. 3. In our simulations, the length of the confidence interval is always less than 5 percent of the associated expected value. In Fig. 4, we show the advantages of exploring the correlations among the locations of mobile users. In this case, the correlation coefficient, r, is equivalent to 90 percent. When the concurrent search approach is used without any priority information, $\lambda_1 = \lambda_2 = 0$ and the maximum stable throughput is around 10. When $\lambda_1 = 1$ but $\lambda_2 = 0$, no correlation information is used and the maximum stable throughput is approximately 19. When the concurrent search approach is used and the correlations are utilized, $\lambda_1 > 0$ and $\lambda_2 > 0$. In this case, the maximum stable throughput is further increased to a value close to 20.

We also study the performance of the proposed algorithm when $N_c = 100$, $N_p = 4$, and $M = 200$. It should be noted that when the sequential paging algorithm is used, the maximum stable throughput is four regardless of the mobility pattern of users. In addition to random walk, we also adopt random walk with drift as our mobility models. For each simulation instance, the proposed algorithm is executed for some duration of time. The duration of time is called the learning period. For each set of parameters, we run the simulation for sufficiently many times. In Fig. 5, we show the impact of drift on the average paging delay. When the location process of a cluster head is a random walk, the length of learning period is 125, and the call arrival rate is 10, the average paging delay is about 4. As the length of the learning period increases to 2,000, the average paging delay decreases to be smaller than 2. When the location process of a cluster head is a random walk, regardless of the length of learning period, the maximum stable throughput is always

TABLE 1
The 95 Percent Confidence Intervals for Fig. 3

number of channels	arrival rate	average delay	lower bound of the 95% confidence interval	upper bound of the 95% confidence interval
1	1	1.9	1.857	1.943
1	2	7	6.994	7.006
2	2	1.54	1.515	1.565
2	3	3.87	3.806	3.934
2	4	8.4	8.371	8.429
4	4	1.5	1.489	1.511
4	6	2.38	2.37	2.39
4	7	3.45	3.428	3.472
4	8	8.8	8.784	8.816
8	5	1	1	1
8	10	1.32	1.314	1.326
8	12	1.49	1.48	1.50
8	16	2.1	2.09	2.11
8	18	2.7	2.688	2.712
8	20	6.8	6.786	6.814

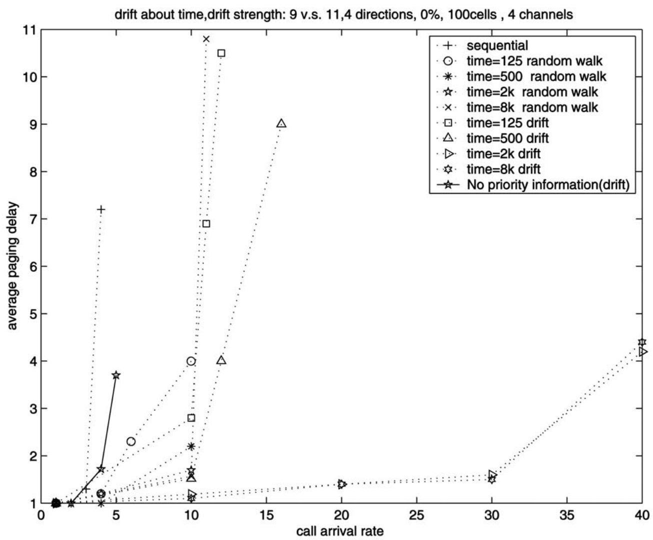

Fig. 5. Random walk versus random walk with drift, 0 percent correlation.

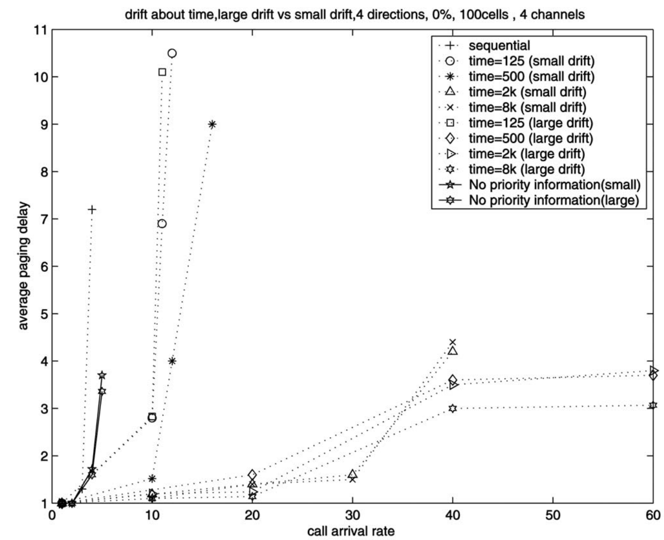

Fig. 7. The impact of the magnitude of the drift, 0 percent correlation.

smaller than 12. When the location process of a cluster head is a random walk with drift and the length of learning period is 125, the maximum stable throughput is close to 12. When the length of learning period becomes 8,000, the maximum stable throughput becomes greater than 40. This means that the proposed algorithm is able to take advantage of the direction of drift to locate mobile users quickly. In addition, it should be noted that our proposed algorithm outperforms the sequential paging algorithm irrespective of the mobility pattern. In Fig. 6, we show the impact of drift on the average paging delay when the correlation coefficient is increased to be 1. Compared to Fig. 5, we find that irrespective of the mobility model, the maximum stable throughput increases as the value of correlation coefficient increases.

In Fig. 7, we show the impact of the magnitude of drift on the performance of the proposed algorithm. We find that the average paging delay decreases as the magnitude of drift increases. The larger the magnitude of drift, the faster the proposed algorithm is able to learn the moving direction of a mobile user. As a result, the average paging delay decreases. Next, we change the correlation coefficient from 0 to 1. In Fig. 8, it is shown that the average paging delay significantly decreases. When the correlation coefficient and the magnitude of drift are both large, the proposed algorithm achieves the best performance. Furthermore, in Fig. 5, Fig. 6, Fig. 7, and Fig. 8, it is shown that the proposed priority heuristic algorithm outperforms the original concurrent search approach in which no priority information is used.

In Fig. 9, we show the impact of the total number of drift directions on the average paging delay. When all of the cluster heads move toward the same direction rather than four directions, congestion is gradually built up in some cells and, therefore, the average paging delay increases. In Fig. 10, we show that when the correlation coefficient decreases to zero, the above conclusion remains valid.

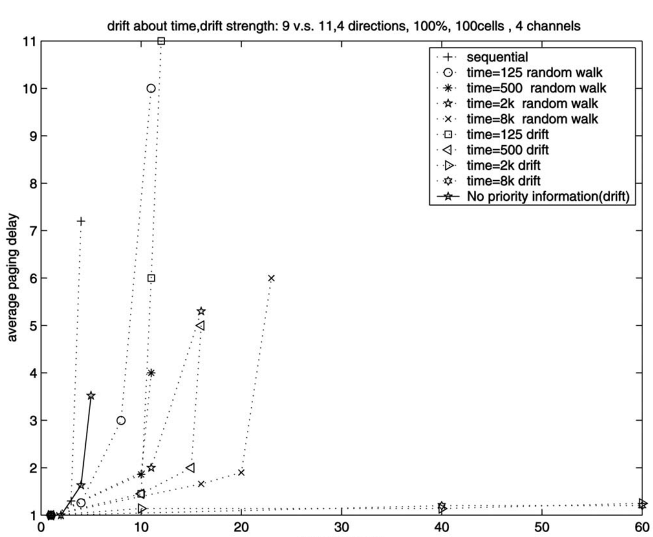

Fig. 6. Random walk versus random walk with drift, 100 percent correlation.

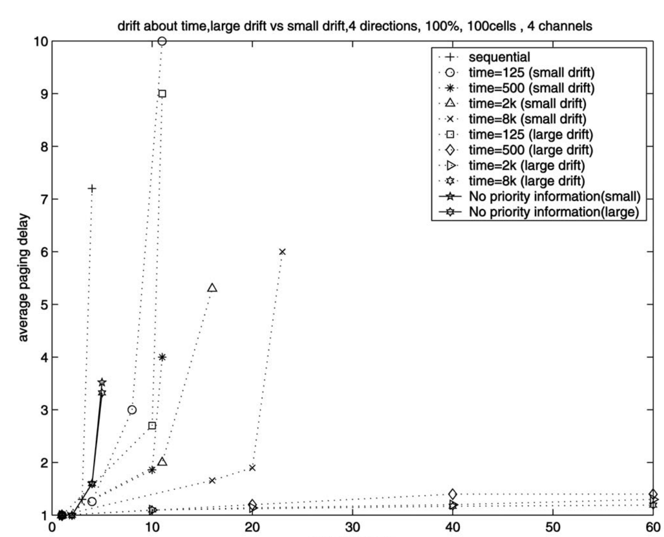

Fig. 8. The impact of the magnitude of the drift, 100 percent correlation.

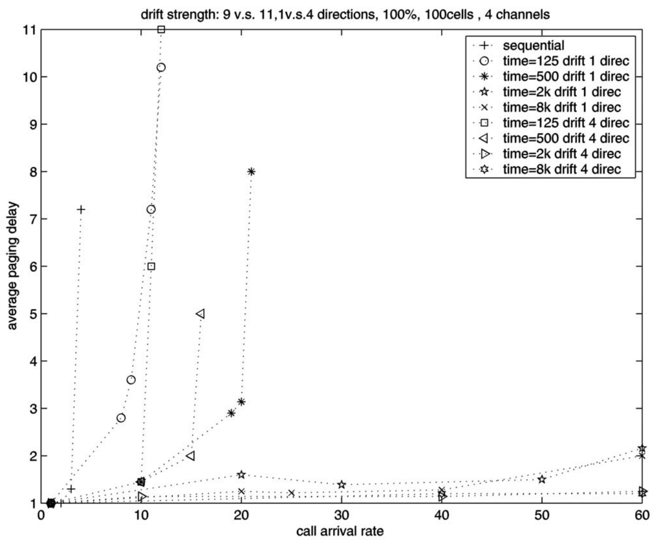

Fig. 9. One drift direction versus four drift directions, 100 percent correlation.

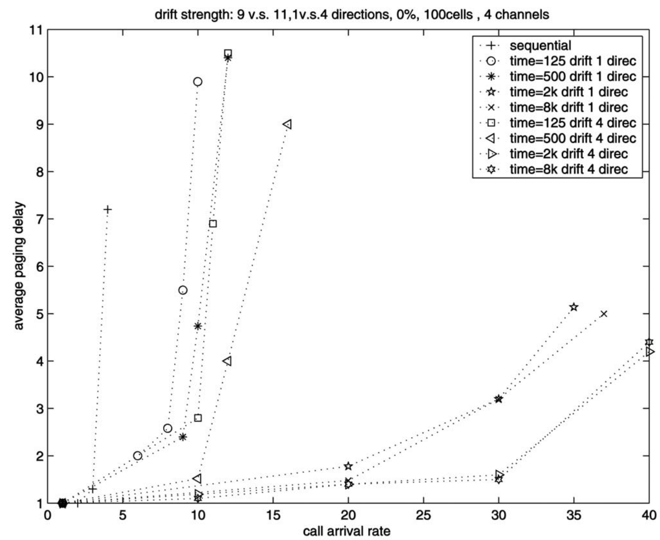

Fig. 10. One drift direction versus four drift directions, 0 percent correlation.

6 Discussions

6.1 A Generalized Mobility Model without Cluster Heads

In the basic mobility model, it is assumed that there exists a unique cluster head in each cluster. In this section, we propose a generalized mobility model for correlated mobile users without any cluster heads.

As in the previous section, it is assumed that the M mobile users in the network are partitioned into α clusters such that the movements of mobile users in distinct clusters are statistically independent. Recall that $Z_n^i = (X_n^i, Y_n^i)$, where $X_n^i, Y_n^i \in \{1, 2, 3, .., w\}$, is the location of the *i*th mobile user at time slot n. In the generalized mobility model, it is assumed that the $\{(Z_n^1, Z_n^2, Z_n^3, .., Z_n^M)\}_{n=1}^{\infty}$ is a discrete-time Markov chain. Recall that there are β_k mobile users in the *k*th cluster, $\forall k \in \{1, 2, 3, .., \alpha\}$. Let $S_1 = 1$ and $S_{i+1} = 1 + \sum_{k=1}^{i} \beta_k$, $\forall i \in \{1, 2, 3, 4, .., \alpha\}$. Without loss of essential generality, it is assumed that mobile user x belongs to cluster k if and only if $S_k \leq x < S_{k+1}$. Namely, mobile users that belong to the same cluster have consecutive indexes. It is not difficult to show that the locations of mobile users in the *i*th cluster at time slot n can be represented by an integer-valued random variable G_n^i. Due to the independence assumption on the locations of mobile users,

$$
\begin{aligned}
&P\{G_{n+1}^1 = y_1, G_{n+1}^2 = y_2, .., G_{n+1}^\alpha = y_\alpha | G_n^1 \\
&\qquad = x_1, G_n^2 = x_2, .., G_n^\alpha = x_\alpha\} \\
&= \prod_{k=1}^{\alpha} P\{G_{n+1}^k = y_k | G_n^k = x_k\} \\
&\forall n, x_1, x_2, .., x_\alpha, y_1, y_2, .., y_\alpha.
\end{aligned}
\tag{11}
$$

6.2 On Identifying The Cluster Heads

There are two types of methods to identify the cluster heads. In the first type of methods, the cluster heads are identified when customers apply for some services. For example, some mobile communications service providers offer a discount to customers who subscribe to the group-talk service [46]. Namely, the price for customers in the same group to call each other is lower than the regular price. To subscribe to the group-talk service, the group initiator has to give a list of all group members to the service provider. A group can be seen as a cluster. The service provider could identify the group initiator as the cluster head. Note that when a group consists of family members, one of the parents rather than the children tends to be the group initiator.

In the second type of methods, the cluster heads are identified based on the calling/called history of mobile users. The proposed priority heuristic algorithm could be modified to facilitate the identification. From the viewpoint of the system, two mobile users with average displacement below a specific value belong to the same cluster. In a cluster, the mobile user with the largest calling/called frequency can be selected as the cluster head.

7 Conclusions

In this paper, we have proposed a novel scheme to locate correlated mobile users in the Universal Mobile Telecommunications System. Given the joint probability density function of the locations of mobile users, we have formulated an integer-programming problem to maximize the expected number of located mobile users in a time slot. We have shown that the integer-programming problem could be solved in $O(2^{N_c \cdot N_p \cdot M})$ time, where N_c is the total number of cells in the network, N_p is the total number of paging channels in a cell, and M is the total number of mobile users in the network.

To derive the joint probability density function for the locations of mobile users, we have proposed a novel mobility model that captures the correlations among the locations of a number of mobile users. In the mobility model, mobile users in the network are partitioned into clusters. Mobile users in the same cluster are statistically correlated, while mobile users in distinct clusters are statistically independent. We have shown that in general, the locations of a single mobile user do not necessarily constitute a discrete-time Markov chain. On the other hand, we have proved that in the mobility model, the locations of mobile users in a cluster form a discrete-time Markov chain.

We have proposed a novel scheme to explore the correlations among the locations of mobile users without explicitly deriving the joint probability density function or solving the integer-programming problem. Since the total number of available paging channels in a cell is limited, a number of calls compete for the paging channels in a cell and a base station has to make a decision on the allocation of the paging channels. In the proposed scheme, each base station makes its own decision independently. The decision is based on two factors. The first factor is the distance from the base station to the last known location of the mobile user corresponding to a competing call. The second factor is the distance between the base station and the last known location of the mobile user with the highest correlation to the mobile user associated with a competing call.

We have used simulations to justify the usage of the proposed scheme. We have shown that exploring the correlations among the locations of mobile users could significantly decrease the average paging delay as well as increase the maximum stable throughput. For example, when there are 36 cells in the network, eight paging channels in a cell, and 200 highly-correlated mobile users in the network, the maximum stable throughput is larger than 16. Compared to the traditional sequential paging scheme in which the maximum stable throughput is 8, this represents a 100 percent increase. We have also studied the impact of mobility on the average paging delay. As the mobility increases, the average paging delay increases. This is mainly due to that the last location of a mobile user becomes a less accurate prediction for the current location of the mobile user. In addition, we have found that the maximum stable throughput when the concurrent search approach is used without taking advantage of the correlations is smaller than the maximum stable throughput when the concurrent search approach is used and the correlations are utilized.

Future work includes further improving the proposed heuristic algorithm. A possible future research direction is to optimally estimate the parameters for the proposed mobility model for correlated mobile users. A promising research direction is to take advantage of the social structure of mobile users to further improve the performance of a mobility management scheme.

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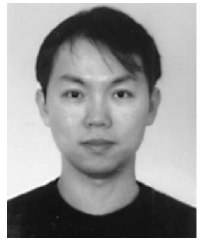

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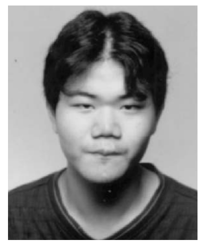

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