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Individual profile graphs for location management in PCS networks ☆

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ABSTRACT

A user's profile, for the purpose of location management in a personal communication service (PCS) network, is formalized as a subgraph of the network graph. This subgraph, the so-called individual profile graph (IPG), is determined after a period of observation with the intent of predicting and codifying the user's diurnal routine. The IPG is easily-motivated, robust, straightforwardly computed from observed data, and, under fairly intuitive assumptions, provably predictive of the user's diurnal routine. An IPG-based paging and update strategy is analyzed. It is shown to significantly improve a straight location area (LA) based strategy that ignores user profiles.

1. Introduction

Subscription to personal communication services (PCS) is growing at an exponential rate owing to the increasing portfolio of services offered over wireless channels. A challenge facing PCS providers is to fulfil demand within a limited frequency spectrum. As cell sizes become smaller and the number of mobile users increases, the signaling cost incurred in both location update and paging increases. Efficient location management per user to minimize update and paging costs, accordingly, becomes vital and has been studied extensively [1–4,6–15].

The geographical coverage area of a PCS network is, typically, partitioned into a number of location areas (LAs), each composed of a group of cells. A mobile user sends a location update when it crosses the boundary of an LA. Upon call arrival, the user is simultaneously paged in all cells of its currently visited LA. Unfortunately, there are two significant inefficiencies associated with the LA-based update scheme. Firstly, an LA comprising a large number of cells consumes significant radio bandwidth while paging. Secondly, location update by users at the time of crossing LA boundaries generates significant data traffic as well, particularly, for those users located near the boundaries.

Recently, location management schemes have been proposed to reduce signaling traffic based upon profiling the mobility pattern of individual users. We discuss here those that motivated the current work.

Xie et al. [15] propose a scheme in which LAs are no longer static but, rather, determined dynamically per user. The authors apply the fluid flow model to represent user mobility. Further, each user's call arrival rate, as well as parameters determined by its mobility, enter into a signaling cost function for that particular user, and an optimal LA size is determined for the user in terms of this cost function.

Tabbane [13] proposes an alternative strategy (AS) for mobile radio communication that focuses on reducing signaling traffic. In AS, the system maintains a profile for each user that consists of a list of LAs ordered to the system's expectation that the user will be found in each. Upon call arrival the LAs in the list are paged sequentially in order of descending expectation. AS actually maintains two sets of profiles – the long-term profile and the dynamic profile. The long-term profile is obtained after a lengthy period of observation, while the dynamic profile changes according to the user's recent call history. The system chooses between either profile to locate the user. Typically, the dynamic profile is used in case of frequent incoming calls.

Pollini and Chi-Lin [7] propose a profile-based strategy (PBS) that evolved from AS. The authors classify users into three categories, in particular, deterministic, quasi-deterministic and random, depending on the predictability of their diurnal routine.

The definitions of user profiles proposed in the literature to date are mostly heuristically motivated. As the authors do not give a rigorous definition of the user profile, obviously they cannot prove

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that it captures aspects of a user's routine. This is the issue that we address here. Our goal is a long-term profile (as in Tabbane [13]), based on a lengthy period of observation, presumed static after formulation, which can, thereafter, be applied to track the user. However, our approach is different from existing ones.

We define, for each user, a graph that we call the individual profile graph (IPG) for that user, whose intent is to predict and codify the user's diurnal routine. The IPG itself is determined as a subgraph of the network graph – the latter consisting of all network cells as vertices and edges representing physical adjacencies of cells.

Our definition of the IPG is simple, robust, easily-motivated, and allows for its straightforward computation from observed data. Further, we prove, under fairly intuitive assumptions, that the IPG indeed captures the diurnal routine of a user. We also show how to incorporate the IPG into a paging and update strategy.

We believe that the IPG is the most natural formulation of a user's profile in the context of location management: on the one hand it arises as a subgraph of the existing network graph, and, on the other, its topology is maximally influenced by the user. This is not the case with LA-based profiling where, for example, the shape constraint on an LA is, typically, system-dependent.

In Section 2 we motivate and define the IPG and prove our claim that it captures a user's diurnal routine. In Section 3 we describe IPG-based paging and update and analyze its performance, showing it to significantly improve a straight LA-based strategy that ignores user profiles. We conclude in Section 4.

2. Individual profile graph

We assume that the network is modeled as an undirected graph $G = (V, E)$ whose vertices V represent cells and edges E represent the adjacency of cells, with no restriction on G other than that its vertices all be of degree $O(1)$. This frees us from the common but somewhat unrealistic constraint that cells in a network are homogeneous in size and shape. Henceforth, we shall use the terms "cell" and "vertex" interchangeably.

A user U that newly enters the system is monitored for some N consecutive days and a daily log is kept for each of these days that records the duration that U spends in each cell. We ignore the technicalities and cost of monitoring U as this is a one-time constant cost incurred per user. Instead, we study how the resulting data can be exploited to develop an efficient update/locate strategy for U.

2.1. Definition

Our approach is to use the log data to define a so-called *individual profile graph* (IPG) of U, denoted G^U, which is subgraph of G that "captures" the diurnal routine of U. The procedure to determine G^U is as follows:

For each vertex $v \in V$, let N_v be the number of days of the N-day monitoring period that U visits v at least once. Normalize, dividing by N, to obtain $n_v = N_v/N$, so that $0 \leqslant n_v \leqslant 1$. The value n_v, that we call the *diurnal weight* of v in U's routine, is the probability that user U visits cell v on a random day.

Given a subset $H \subset V$, let the *induced subgraph* of H, denoted $in(H)$, be the subgraph of G whose vertex set is H, and whose edge set consists of edges in E both of whose end vertices lie in H.

For $0 \leqslant \mu \leqslant 1$, define the subgraph G_μ of G as follows:

$$G_\mu = \text{in}(\{v \in V : n_v \geqslant \mu\}) \tag{1}$$

In other words, G_μ consists of cells with diurnal weight at least μ and edges connecting such cells. Let the sequence

$$\mu_1 > \mu_2 > \ldots > \mu_r \tag{2}$$

be the sequence, in descending order, of distinct values of n_v, for $v \in V$.

We get a corresponding sequence

$$G_{\mu_1} \subset G_{\mu_2} \subset \ldots \subset G_{\mu_r} \tag{3}$$

of subgraphs of G, where the successive containments are strict.

These subgraphs may not all be connected – an evident requirement of an IPG. Accordingly, let

$$G_{\mu_{i_1}} \subset G_{\mu_{i_2}} \subset \ldots \subset G_{\mu_{i_s}} \tag{4}$$

be the subsequence of Sequence (3) of connected graphs.

We wish to choose U's IPG to be the one of $\{G_{\mu_{i_k}} : 1 \leqslant k \leqslant s\}$ that represents a "boundary" beyond which diurnal weights drop significantly – intuitively, that $G_{\mu_{i_k}}$ outside of which U rarely travels on a daily basis. Moreover, we wish to make this choice in a robust manner. Accordingly, consider the successive differences

$$\mu_{i_1} - \mu_{i_2}, \mu_{i_2} - \mu_{i_3}, \ldots, \mu_{i_{s-1}} - \mu_{i_s} \tag{5}$$

and let $\mu_{i_K} - \mu_{i_{K+1}}$ be the *maximum* of these (if there is more than one maximum term in the sequence, choose $\mu_{i_K} - \mu_{i_{K+1}}$ to be the leftmost one).

Define the user's IPG to be

$$G^U = G_{\mu_{i_K}} \tag{6}$$

Fig. 1 shows a network graph G that is an 8×8 grid graph and the IPG G^U (shown bold) of a hypothetical user U whose diurnal weights are indicated in each cell. The derivation of G^U is indicated in Fig. 2. In particular, the ten distinct values of the diurnal weights in G are:

$$0.96 > 0.92 > 0.82 > 0.76 > 0.70 > 0.66 > 0.64 > 0.18 > 0.06 > 0.00$$

Fig. 2 shows separately the 10 subgraphs

$$G_{0.96} \subset G_{0.92} \subset G_{0.82} \subset G_{0.76} \subset G_{0.70} \subset G_{0.66} \subset G_{0.64} \subset G_{0.18} \subset G_{0.06} \subset G_{0.00}$$

of which the following subsequence is of connected subgraphs

$$G_{0.96} \subset G_{0.92} \subset G_{0.66} \subset G_{0.64} \subset G_{0.18} \subset G_{0.06} \subset G_{0.00}$$

which proves that the IPG G^U is $G_{0.64}$.

Observations

(1) Our current definition of the IPG is coarse in that it uses only per-day data and not intra-diurnal data, that is assumed available as well, in particular, the user's mobility pattern during a day. We do, however, utilize intra-diurnal data in our paging strategy discussed in the next section.

(2) Our current definition of the IPG is independent of any grouping of cells into LAs, if, in fact, the network be configured in such a manner. A straightforward extension is to simply replace cells with LAs in the construction of the IPG. However, more sophisticated approaches are possible – we discuss LAs in the context of IPGs in the concluding section.

(3) IPGs are particularly suitable for users that would be classified as either deterministic or quasi-deterministic in the taxonomy introduced by Pollini and Chi-Lin [7]: these are users whose daily mobility pattern tends to be repetitive. Random users, on the other hand, almost by definition, do not yield an IPG of any value.

2.2. Validity

We prove next that, under certain fairly intuitive assumptions, the IPG G^U indeed captures U's diurnal routine.