An Activity-based Mobility Model and Location Management Simulation Framework

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Abstract - **To cope with an increasing number of subscribers, modern cellular telecommunication networks have been employing smaller, lower-power cells. The smaller diameter and larger number of these cells, however, result in increased signaling requirements for location management purposes. Several location management schemes have been proposed to improve the performance of such networks, but a fair assessment and comparison of their performance is difficult without a realistic mobility model, since the performance of location management schemes depends considerably on subscriber mobility patterns. This paper discusses a stochastic mobility model based on daily activity patterns, providing a realistic balance between completely deterministic and completely random mobility models. The mobility model is implemented within a Java simulation framework, which permits flexible implementations of mobility models and location management algorithms for direct and objective comparisons.**

I. INTRODUCTION

The cellular telecommunications market around the world has seen tremendous growth. For operators, this success has come with the challenge of meeting the infrastructure and quality of service requirements generated by increased network usage. Modern cellular networks thus employ frequency reuse among increasingly smaller, lower-power cells to increase overall system capacity and coverage. The lower transmission power also results in lower interference ratios and longer battery life for the mobile stations.

One of the tradeoffs is increased signaling requirements for location management, due to the smaller size and larger number of cells, thereby reducing the bandwidth available for revenue-generating traffic channels. Location (or mobility) management is concerned with the procedures required to enable the network to maintain location information for each mobile terminal, in order to efficiently route incoming calls. The two fundamental procedures which comprise location management are location updates and pages. Location updating is initiated by the mobile station, and informs the network of the subscriber's current location area. Paging is initiated by the network when an incoming call arrives, in order to determine the exact cell that the mobile station is camped on and set up a radio channel. Paging messages are broadcast in one or more paging areas, normally contained within the current location area. Algorithm performance is typically measured using the number of location updates performed and the number of cells paged, both of which should be minimized to reduce the amount of bandwidth used for location management-related signaling. Although handovers are not normally considered part of location management and will not be discussed here, the proposed mobility model and simulation framework can be extended to allow for handover performance comparisons.

Several location management schemes [1,2,3,4,5,6,7, 8,9] have been proposed to improve upon the performance of existing location management algorithms. The performance of particular location management schemes depends to a large extent on the mobility patterns of cellular subscribers. Therefore, to properly assess and compare the performance of current and proposed location management schemes, realistic mobility models are required. Some proposed algorithms use variations of statically assigned location areas, or layers of location areas, while other proposals use dynamic or individualized location management algorithms. The use of subscriber profiles, maintained at the mobile station and/or the network databases, is also relatively common. As a result, some algorithms are well-suited to random mobility, but may be far from optimal under more regular mobility patterns, while the opposite may also be true.

To allow for objective evaluations of such diverse algorithms, a mobility model was developed with the goal of providing realistic mobility patterns for individual subscribers. The model is based on activity pattern theory borrowed from related work in traffic engineering and social science, and using raw data from regional planning travel surveys. The principle behind the model is that, through statistics derived from travel surveys, there are certain probabilities associated with one activity following another activity, based on certain parameters such as time of day and socioeconomic status. Each activity has a duration and location (at a radio cell level of granularity) associated with it. The mobility model has the necessary degree of randomness, but also reflects the routine in daily activity observed by social scientists and anyone who has suffered through the morning and evening rush hour.

A flexible object-oriented simulation framework was developed to implement and compare different mobility models and their interaction with different location management algorithms. The simulation output provides both detailed descriptions of subscriber movement and call arrivals, as well as summarized observations of the total number of cells crossed and cells paged for each subscriber.

These metrics allow the direct performance comparison of different location management algorithms under different mobility models.

II. Overview of Mobility Modeling

A mobility model, in the context of location management, is a model of the daily movements of mobile subscribers, or more precisely, the daily movements of registered mobile stations. Such a model is of paramount importance in mobility management studies. The number of generated paging and location update messages, required for comparisons of the efficiency of different location management schemes, depends fundamentally on user mobility patterns. This section gives a brief overview of travel demand models and transportation theory from the field of transportation planning, which were used by the proposed activity-based mobility model.

A. Travel Demand Modeling Overview

In the areas of transportation planning and traffic engineering, various transport models are used to describe and forecast travel demand, usually in terms of trips taken by households, and typically concentrating on urban areas. The particular model chosen depends on several variables, particularly the availability of appropriate data and the specific application of the model. The main purpose of most transport models is to analyze observed urban travel behavior and its relationship to certain socioeconomic variables, in an effort to forecast future travel behavior in the face of population growth and upon implementation of different transport policies or services.

A basic element of transportation modeling is the trip. A trip is usually defined as a one-way movement of one person from an origin to a destination, utilizing one mode of transportation. Trips are often categorized by the purpose behind the trip, such as work, shopping, and return home. Other important concepts in transportation modeling include the concept of traffic zones. Traffic zones represent the aggregate socioeconomic features and spatial structure of a geographical area, such as a municipality, by usually no more than a few hundred traffic zones which can range in size from a few hundred square meters to several square kilometers. Trips are assumed to originate and terminate at a single fixed point within a traffic zone called the centroid. The definition of traffic zones depends on the particular goals of a transportation study, and is usually a compromise between representational accuracy, analytical complexity, and availability of data.

There are several different approaches to travel demand modeling. All integrated classical models, however, attempt to describe and forecast the four basic components of travel demand [10, 11, 12]. Some methods view and model each component separately, while others combine two or more steps.

Trip generation – Estimation of the total number of trips T_i originating from zone i and/or the total number of trips T_j terminating at zone j. In practice, the trips are classified by trip purpose, such as work, shopping, or social/recreation, and are often grouped into home-based or non-home-based trips, depending on whether one end of the trip is at the home. Trip generation may be based on zonal averages, or it may be based on type of household.

Trip distribution - Given the total number of trips originating in a given zone T_i, calculation of T_{ij}, the number of trips from each zone i to every other zone j. The number of trips entering a particular zone can similarly be distributed to all other origin zones.

Modal split - Modal split determines the relative ratio of the different transportation modes (e.g., car or transit) used for each T_{ij}.

Trip assignment - Given the number of trips T_{ijm} from a zone i to a zone j using a mode m, map the trip route onto the existing or proposed transportation infrastructure. The selected route is typically the one with the smallest generalized cost, usually some combination of time, distance, speed, and convenience.

B. Aggregate Models

Aggregate models are the earliest of the travel demand models, and are still being used in practice. They attempt to model the behavior of aggregations of the population, based on average socioeconomic indicators, such as age and income, on a per traffic zone or per household type basis. The classical transport model is the most basic aggregate model, with many modifications having been made in different studies. This model has been used since the 1960s to forecast travel demand, and various techniques and submodels [11,12,13] have been developed for determining the variables for each of the four elements of travel demand.

Treating each of the four elements of travel demand independently, however, has no compelling theoretical support. Direct demand models attempt to estimate trip generation, trip distribution and modal split simultaneously [11], possibly together with trip assignment, using products of calibrated dependent variables. Although calibration of direct demand models is simpler and more intuitive than calibrating the individual submodels of the classical model, there are both theoretical and practical disadvantages, such as the large number of parameters required.

C. Disaggregate Models

The classical travel demand model has a number of shortcomings that have been recognized for some time. One of the main criticisms is that it does not represent a coherent theory of travel behavior [10]. Aggregate models describe or replicate aggregate travel demand, without explaining it.

Since aggregate models are basically correlative, large quantities of input data are required for accuracy, so such studies tend to be expensive. Disaggregate models [10,11,13,14] have attempted to improve travel demand analysis by modeling the behavior of individuals, rather than socioeconomic groups.

1). Discrete choice models

One of the more common approaches to disaggregate travel demand is the discrete choice model, which is based on random utility theory borrowed from microeconomics. The underlying principle of this theory is that individuals will attempt to maximize their utility, or minimize their disutility, when making travel-related choices. The utility functions [11,15] for different alternatives in a given choice set, for each decision-maker, are represented as a linear function of socioeconomic and alternative-specific variables, together with a random component. The random component is used to incorporate individual tastes and measurement error.

Discrete choice models offer a more realistic and behavior-based approach to travel demand, but they also suffer from a number of drawbacks. The definition of a choice set poses difficulties when dealing in practice with many discrete options such as trip destinations. Given more than a few alternatives in a choice set, the mathematics quickly become overly complicated. Aggregation of the results, which is necessary for practical forecasting, becomes difficult in cases where the models are not linear.

2). Activity-based approaches

Travel demand is generally considered a derived demand, since there is ultimately some other purpose for which travel is undertaken. Travel is therefore a means to an end, rather than an end in itself, except for relatively rare cases such as pleasure drives. A description of the daily (or longer term) activity patterns of individuals and households will therefore provide a deeper understanding of travel behavior, and thus better descriptions and predictions of travel, given certain spatial and temporal constraints. There has been a fair amount of work in recent years into activity-based approaches to travel demand, although there is no dominant methodology. The different approaches share some common features, including a focus on patterns of behavior, rather than on statistics of individual trips; consideration of the timing and duration of activities and travel, instead of just peak traffic; and consideration of interpersonal constraints between household members [16,17,18,19,20]. Although there remain several challenges in the activity approach, such as the handling of complexity involved in travel behavior, the gathering of relevant and detailed survey data, and the aggregation of results to allow forecasts. the approach has much potential for providing a deeper understanding of travel behavior and hence better forecasting techniques.

III. Proposed Activity-Based Mobility Model

The basic goal of the mobility model is to provide, at the level of individuals, a set of paths traversed on a daily basis, over an extended period of time to permit the evaluation of location management algorithms which rely on building user profiles over time. After reviewing the relevant literature, it was decided that the approach most closely matching the requirements, in terms of intuitive theoretical basis, simplicity, ease of implementation, and flexibility, was a modified activity-based approach. The driving parameter in the model is the concept of activity, which is equivalent to trip purpose, a parameter typically included in travel surveys conducted by regional traffic planning departments.

Each activity has an associated time of day, duration, and location (at the level of a radio cell). An activity is selected based on the previous activity and the current time period. The probability of transition from one activity to another uses the activity transition matrix. Once the next activity is selected, its duration is determined using the activity duration matrix. Finally, the location of the activity is selected, based on certain heuristics and the type of activity. Since the current location of the subscriber is already known, once the location for the next activity is selected, the intermediate route (in terms of cells crossed) and the total distance are determined from a geographical lookup table. Using a user-defined system-wide average speed, the time spent in each intermediate cell is calculated. The subscriber stays in the destination cell for the duration of the activity, and the sequence is repeated. In terms of travel demand theory, this model integrates the trip generation, distribution, and assignment functions, in a disaggregate scheme. Trips are assumed to use motorized transport on existing roads, so modal split was not required. This assumption is justified since the vast majority of trips in most travel surveys use some form of motor vehicle as the mode of transport [21]. The output from the model is thus a trace of the daily movement of individual cellular subscribers over a period of several days, in terms of cells crossed and time spent in each cell.

A. Input Data

The activity transition and duration matrices used by this mobility model were derived from the trip survey [21] conducted by the Regional Municipality of Waterloo in 1987. For this survey, a travel diary was completed by each household member over 5 years of age, in which details on all trips taken during the survey day were recorded. Included for each recorded trip were the trip start and end times, the trip purpose at the origin and destination, and employment or student status. Trip purpose was used in the traffic survey to classify the reason for the trip into one of nine possible categories:

1. work
2. work-related
3. school
4. serve passenger
5. shopping
6. social/recreation
7. personal business
8. return home
9. other

After validation, the trip survey data was manipulated by an external program to obtain data directly applicable to this model. To incorporate time-of-day into the model efficiently, a day was divided into twelve equal segments, or time periods. Time periods are used to statistically aggregate data from the trip survey.

Each simulated subscriber has certain characteristics, such as person type. Four categories of person type were defined, similarly to [22]. This categorization attempted to create groups of somewhat similar subscribers, with similar mobility patterns, using data available from the trip survey. The four categories were:

- Full-time employed outside the home
- Part-time employed outside the home, but not a student
- Student, secondary or post-secondary, possibly employed part-time outside the home
- Not employed outside the home, and not a student

1). Activity transition matrix

The activity transition matrix is an empirical distribution of transitions from one activity (or trip purpose in the trip survey) to another, recorded as a four-dimensional array. The distribution is indexed by the subscriber's person type, the current time period, and the previous activity.

TABLE 1. SAMPLE DATA FROM THE ACTIVITY TRANSITION MATRIX

User-group	Time-period	Previous Activity	Next Activity	Cumulative probability
1	4	8	1	0.351724
1	4	8	2	0.393103
...	...	...	...	...
1	4	8	8	0.962345
1	4	8	9	1.000000
1	4	9	1	0.000000

Associated with each entry is an empirical cumulative distribution of the transition probability to the next activity, as shown in Table 1. Implicit in this model is the assumption that activity linkages depend on individual characteristics and on the time of day (i.e., time period). This assumption has been supported by other studies [23].

2). Activity duration matrix

The activity duration matrix is also a four-dimensional array indexed by person type, time period, and current activity, giving a cumulative probability distribution of the different activity durations that were observed, as shown in Table 2. The duration of a particular activity, aggregated into 5 minute intervals, can be derived from chronologically sorted trip survey records by calculating the difference between the arrival time of one trip record, and the departure time of the following trip record. The previous record's destination (arrival) purpose and the subsequent record's origin (departure) purpose must be equal, otherwise the pair of records is rejected.

TABLE 2. SAMPLE DATA FROM THE ACTIVITY DURATION MATRIX

User-group	Time-period	Activity	Duration	Cumulative Probability
0	7	6	400	0.974359
0	7	6	460	0.987179
0	7	6	540	1.000000
0	7	7	0	0.125654
0	7	7	5	0.235602
0	7	7	10	0.413613

In addition, when the origin purpose of the earliest recorded trip matched the destination purpose of the last recorded trip for a particular subscriber, the duration of that purpose (i.e., overnight duration) was assumed to be valid and was recorded. In almost every case, the first recorded trip started at the home, and the last recorded trip ended at the home (i.e., the purpose or activity was home).

B. Algorithm Description

The proposed algorithm uses the input tables described above to generate trips based on activity patterns. A subscriber is initialized with a current activity (home), together with other subscriber-specific attributes, such as the type of subscriber (full-time employed, etc.), the home, school, and work locations (cells), and whether the work location is fixed throughout the day. Given these inputs, the algorithm can derive the next activity, its location, and its duration, as outlined in Figure 1. This output is then used by the simulation framework to determine the path taken (and cells crossed) to get to the destination, as well as the relative timing of the cell crossings. The cell crossings, and the current location of the subscriber (which is always known) are used by the different location management algorithms to determine location updates and the number of cells paged for incoming calls, which are the key metrics for comparing location management algorithms.

Given the current activity, the current time period, and the subscriber type, the next activity is randomly selected from the corresponding entries in the activity transition matrix. Together with the person type and the current time period, the selected next activity is used to determine the duration of the activity, using the activity duration matrix.

The next destination cell also depends on the selected activity. If the activity is work (for fixed work locations), school, or home, the subscriber's stored locations are used. The location returned for the other activities (except for shopping) is a uniformly distributed random number representing a cell. For shopping, the possible destinations are limited due to shopping location constraints, as well as habit and convenience among individuals. Therefore, shopping may be more realistically modeled in terms of zonal retail employment [24], or distance to shopping location [12]. The method used in this simulation is a combination of these two approaches. The zonal retail employment (aggregated to form cell-level retail employment) is divided by the distance from the current location to the target cell. The destination cell is randomly selected from the top five target cells. Intuitively, this method prefers shopping district cells which are closer to the current location of the subscriber.

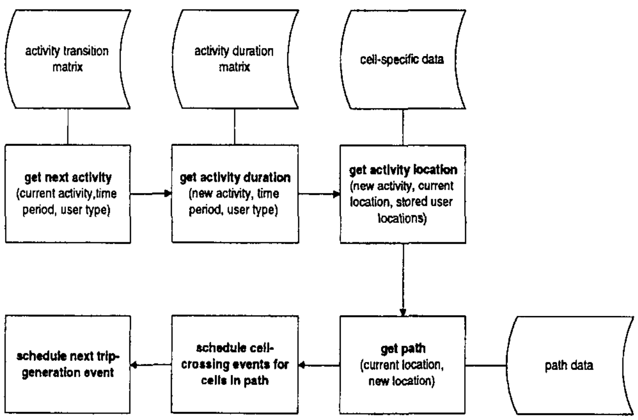

Figure 1. MobilityEvent handler flowchart for mobility model

Using the subscriber's current cell and the selected destination cell, the path and total distance are obtained from external data. The total distance is divided by a user-defined system-wide average speed to calculate the total time, which is divided by the number of crossed cells to derive the cell crossing time. An assumption was made that cell crossing times are equal for all the intermediate cells; endpoint cells have half of the cell crossing time each.

IV. SIMULATION FRAMEWORK

An object-oriented discrete-event simulation framework, written in Java, was used to implement and compare different mobility models, including the proposed model, with different types of location management algorithms. The simulation is based on mobility models generating trips from the current cell to a destination cell, represented as a sequence of cell-crossing events for different subscribers. In addition, a fixed number of daily incoming call events are generated for each subscriber. Together, these events translate into location updates or cells paged, depending on the location management algorithm. Each subscriber is associated with exactly one mobility model. Each cell crossing event is concurrently handled by the location management algorithms as a potential location update, and logged as required. Incoming call events for each subscriber are handled by the location management algorithms as pages, and logged. Detailed logs are produced of all mobility and incoming call activity, as well as summarized logs providing the total number of location updates and cells paged for each subscriber.

A. Overview of Framework

The Subscriber class contains all subscriber-specific attributes and methods required by the different mobility models. The three main event classes in the mobility simulation are MobiltyEvent (or trip-generation event), CellCrossingEvent, and IncomingCallEvent. Each is represented as a subclass of the abstract Event class, which contains shared attributes such as the time of the event and the associated Subscriber object. The MobilityEvent class is abstract and is further subclassed into classes representing the different mobility models. The proposed mobility model is described in the next section. The main function of each of these subclasses is to generate CellCrossingEvents for a given subscriber, based on the implemented algorithm. It should also instantiate and queue a new mobility event to continue the simulation.

CellCrossingEvent objects call the LocationManager object to test for a location update in all the different location management algorithms being compared, and perform a location update if required. An IncomingCallEvent object, whose occurrence indicates a call arrival for a particular subscriber, calls the LocationManager object to page a Subscriber in all the different location management algorithms being compared. The LocationManager object manages access to all location management algorithm objects, which each implement the LocationAlgorithm interface.

The EventScheduler class maintains the future event list, and provides methods to add and remove events in chronological order. Removing an event indicates the 'occurrence' of a particular type of event, and executes the corresponding Event handler() method, which performs the majority of the work (e.g., generating additional events, or writing output to the log files). An initial MobilityEvent and an initial IncomingCallEvent start the simulation for a given subscriber, which continues until a user-defined simulation termination time.

Additional classes provide helper objects. The CellGeography class manages the simulation's geographical layout, providing path and distance information between cells, as well as cell-specific information. The Trip class is used by the proposed mobility model implementation (specifically, the MobilityEvent subclass TripEvent) to generate activities, their location, and their duration.

The simulation uses an external text file to initialize global variables and each subscriber group. A subscriber group is associated with a particular mobility model, and has certain model-specific parameters. Each subscriber group definition is used to instantiate a user-defined number of subscriber objects. The proposed mobility model requires user type and work location variability parameters. All subscriber groups require the number of daily call arrivals. The simulation itself runs for a user-defined number of simulated days. Output includes both detailed (optional) and summarized logs.

B. Class Descriptions

1). MobilityEvent class

The classes implementing the mobility models all inherit from this class. The purpose of these classes is to generate CellCrossingEvents, corresponding to the trips or movements taken by the simulated Subscribers. Different mobility models may require different inputs. After the CellCrossingEvents are instantiated and queued, another MobilityEvent is generated and queued, representing the next trip/movement to be executed by the specific Subscriber. In addition to the implementation of the proposed mobility model, two random mobility models have also been implemented;

2). CellCrossingEvent class

When a CellCrossingEvent occurs (i.e., the event is pulled from the global event queue, and its handler() function is called), the checkUpdataLocn() function of the LocationManager object is called, which in turn calls each of the location management algorithms under evaluation. The exact location update actions depend on the particular algorithm. The Subscriber object is a parameter can be used to access subscriber-specific stored information (e.g., location registers). Details of any location updates, such as the time and cell in which they occurred and the cells which comprise the new location area, are logged to an external file, as required, by the LocationManager class.

3). IncomingCallEvent class

Independent of any movement or specific mobility model, a user-defined number of incoming calls, represented by IncomingCallEvents, arrive every 24 hours for a Subscriber. Call arrivals are not modeled using the typical Poisson arrival process, since that model is not very realistic for individual subscribers receiving calls. A subscriber is much more likely to receive a call at 2 pm than at 2 am, a fact not accounted for by a Poisson model. A simulated day is divided up into three segments, each with a corresponding percentage of daily call arrivals as shown in Table 3. This approximately represents the observed busy periods during the morning and mid-afternoon, and slow periods during late night and early morning.

Similarly to the CellCrossingEvent, when an IncomingCallEvent occurs the performPaging() function of LocationManager is called, which in turn calls all evaluated algorithms to page the Subscriber. The exact paging actions depend on the particular location management algorithm implementation. The required number of paging messages (i.e., cells paged) are logged to external files.

TABLE 3. PROBABILITY DISTRIBUTION OF INCOMING CALLS OVER TIME OF DAY

Time of day	Probability of incoming calls
00:00 to 08:00	0.20
08:00 to 18:00	0.50
18:00 to 24:00	0.30

4). Subscriber class

The proposed mobility model describes individual subscriber movement, and so certain information must be maintained for each subscriber. The Subscriber class also maintains group parameters for random mobility models. In transportation theory, individuals (or groups) can be categorized by many different parameters, such as income or car ownership. To avoid unnecessary complexity, yet still differentiate between different groups, a person type variable was defined for the proposed mobility model. Also maintained for every Subscriber object is the current location. Other information required by implemented location management algorithms or mobility models can also be included. This encapsulation of subscriber-specific data allows multiple simulated subscribers to run concurrently.

5). LocationManager class, LocationAlgorithm interface

Location management algorithm classes implement the interface LocationAlgorithm, which requires methods to check for and perform location updates (checkUpdateLocn()) and to perform pages (performPaging()). In addition to these methods, a class may contain additional private methods or variables, such as location registers (e.g., HLR). A simple HLR construct is used to store subscriber-specific data, such as the current location area, required by an algorithm. Each type of location management algorithm is defined by one class implementing the LocationAlgorithm interface, although there can be one or more location management objects instantiated from that class. The LocationManager object (defined as static, so there is only one) keeps track of all location management objects, and provides a public 'interface' to the specific LocationAlgorithm objects. The abstraction mechanism provided by LocationManager separates the details of the number and type of location management algorithms from the mobility model itself.

6). CellGeography class

The static CellGeography class maintains cell-specific information, as well as path and distance information, which is read in from external files. This is required to create paths, including intermediate cells, for all generated trips, indireclty allowing a Subscriber's current cell to be known at all times (i.e., even between destinations). This concept of intermediate cells is used by the proposed mobility model to maintain the statistical distribution of time spent in different cells.

The routing and distance information was derived for the actual street grid layout of Waterloo Region, using geographical information system (GIS) software. Superimposed on the street grid was a theoretical layer of radio cells. Cells are groups of adjacent traffic zones as defined by the Region of Waterloo Planning Office. The assignment of traffic zones to cells was somewhat arbitrary, but followed some basic rules, such as making cells as convex as possible, and making cell size roughly inversely proportional to road and population density. Each cell was represented by a centroid, a point roughly in the center of a cell, and connected to the street grid. The path taken from one cell to another was in practice from one centroid to another. Using the GIS minimum path function, the minimum distance between each pair of centroids was calculated, and the cells crossed by this minimum path were recorded manually.

V. Conclusions and Future Work

A mobility model was developed which simulates the daily movements of mobile subscribers (in terms of a sequence of radio cells), incorporating realistic, individualized activity patterns and geographical focal points. The mobility model was implemented within an object-oriented simulation framework, written in Java, which allows for a flexible and objective comparison of different mobility models and location management algorithms. The output of the simulation is the number of location updates and cells paged, for each subscriber (corresponding to a mobility model) and each location management algorithm. Given these metrics (which can be combined to form total cost), direct and objective comparisons can be done between the different location management algorithms, and their interactions with different types of mobility models.

The simulation framework has been used to compare both static and dynamic location management algorithms, using the activity-based mobility model, as well as a random mobility model [25]. The results obtained indicate that the underlying mobility model does indeed play a critical role in the relative comparisons of different algorithms.

Possible future uses and extensions of the mobility model include modification of the model to allow performance comparisons between different handover algorithms. This would require enhancing the simulation framework to maintain knowledge of the duration of calls (incoming and outgoing) as the subscriber moves from cell to cell. Call arrival and/or wireless data usage patterns also influence the performance of the location management schemes. We therefore plan to examine the usage patterns of wireless data users to complete a realistic simulation environment. Once the necessary data collection and processing are complete, the data files and simulation core can be provided to interested parties.

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