Enhancing Mobile QoS Based on Movement Contracts

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***Abstract*— Resource management for individual flows can significantly improve quality of service (QoS) in mobile cellular networks. However, its efficiency depends on the availability of information about the movement of mobile terminals. Movement prediction can potentially provide this information, but is costly if performed by the network and usually assumes a certain movement model, which may not adequately reflect each individual user's behavior. Instead, we propose the concept of *movement contracts*, where a mobile terminal specifies its movement to the network, which in return provides a better QoS as long as the provided specification is sufficiently accurate. We describe approaches to specify the spatial and temporal aspects of movement with a parsimonious parameter set and evaluate these approaches through simulations. We find that movement contracts can significantly reduce both session blocking and handover dropping probability simultaneously, whereas existing approaches have to make a tradeoff between these.**

I. Introduction

Mobile cellular networks of the third generation and beyond promise to deliver high quality rich media content to mobile users. Yet, user mobility leads to frequent handovers between access routers. As cell sizes decrease to accomodate the rising capacity requirements, the handover rate increases. This in turn can have a strong negative impact on the perceived quality and associated with it the customers' acceptance of these new services. The effects of a handover between access routers are twofold:

1) During a (hard) handover there might be an interruption of service due to rerouting, possibly incurring losses.
2) After a handover, service characteristics, such as bandwidth, delay, and jitter might change considerably due to higher traffic loads in the new cell, for example.

How a session is affected by a handover to a cell with insufficient available resources depends on the application that initiated it. In the best case, the application can adapt to a lower quality as long as a minimum acceptable QoS can be met. In the worst case, it cannot tolerate any deterioration of the service, and the session is simply dropped. This is still the case with voice services in current mobile cellular networks.

Both handover drops and frequent QoS changes due to handovers should be avoided by the resource management and call admission control of access routers. The respective approaches can typically be divided into class-based and individual flow-based approaches:

- Class-based resource management (e.g. [1]) assigns each session to a class—distinguishing, for example, between originating calls and handover calls and/or between real-time and non-real-time services—and gives all sessions of the same class the same treatment. A popular mechanism is the guard channel (e.g. [2]): it keeps a pool of bandwidth resources exclusively for handover sessions assuming that handover sessions should be given strict priority over new sessions. Many proposed strategies adapt the size of the guard channel dynamically based on aggregated information about observed past traffic loads, possibly also considering traffic in neighboring cells.
- Individual flow-based resource management (e.g. [3], [4], [5]) attempts to provide each session with its individual bandwidth requirements, usually by reserving the appropriate resources for the session in advance. This approach requires information on the movement of the respective mobile host.

The latter approach can provide harder QoS guarantees, because it limits the handover dropping probability per mobile node instead of only for the average member of a service class, but requires per-user state in access routers. Furthermore, per-flow reservations are sometimes deemed to perform poorly when compared to class-based resource management when a user's movement is not known [6]. However, we regard resource reservations as an interesting option for mobile network operators, because a) the efficiency increases with improved knowledge about the user movement [7], b) reserved resources that are not claimed can be re-used by mobile nodes with lower QoS requirements (passive reservation approach proposed in [8]), and c) we envision such strong QoS guarantees as premium service for those users who are willing to *either pay more* for their increased resource demands *or* to make a similar effort by *providing* the network with *information about their movement*.

Various contributions have been made that exploit information about the spatial component of user movement (*where* a user will be) to improve the efficiency of resource reservation. In the scheme proposed in [5] a mobile user has to provide the network with a list of cells (called movement specification) in which reservations are made for the duration of the whole session. Chang et al. [1] suggest to exploit the path information from car navigation systems. Other approaches base predictions on a user's movement history (e.g. [9]).

On the other hand there is little work to describe the temporal component of user movement (*when* a user will be at a certain location). This information is required to determine the optimal reservation schedule for an access router's resources, for example using the dynamic programming algorithm presented in [10]. One possibility to obtain this information is by movement prediction, which has several disadvantages, though. First of all, movement prediction is costly in terms of processing and would have to be performed repeatedly by the network for all mobile hosts. Secondly, movement prediction is often restricted to a short range, for example the next street corner, which means that resource management cannot plan ahead efficiently. Finally, a movement prediction assumes a certain movement model, which may not reflect each user's behavior accurately: if a user wanted to comply with the model, he would have to restrict his movement—if he is aware of the model at all.

Instead we propose to give mobile terminals the option of providing the network with a spatial and temporal specification of their respective user's movement at some point prior to the start of a session. The network, in exchange, can provide the user with an improved level of QoS as long as the given specification is sufficiently accurate. This agreement, which we call *movement contract*, can be re-negotiated at a later point in time during the session to adapt to changes in a user's plans as well as to varying environmental conditions, such as stops at traffic lights. We will show how user movement can be specified using a small set of parameters that can be inferred (automatically) by a mobile terminal from historical data such as the user's past movement, but which at the same time allows the network to calculate small time windows in which the user is expected to pass through a given network cell.

In the following section, we first give a high-level system view of a possible implementation. We then outline how user movement can be specified with a small number of parameters, proposing two different specification approaches and two methods to compute their required parameters. In Section III, we present the environment and the results of our simulations to measure the performance of the movement specifications. Finally, we draw conclusions and provide an outlook on future work.

II. Controlling Handover Dropping through Movement Contracts

A. System View

Central to the concept of movement contracts is the idea that a user can provide more accurate information about his intended movement than the network can infer by pure observation—as is the case with movement prediction. From the viewpoint of the user the incentive for disclosing this information results from an improved QoS or a lower service charge that the network can grant in exchange for being able to manage resources more accurately. Furthermore, movement contracts shift the complexity inherent in movement prediction out of the network and into the mobile terminals, leading to increased scalability. Passing information about intended movement to the network might raise privacy concerns. However, the disclosed information could just as well be collected by the network during a session and—in case of movement prediction by the network—might even have to be stored for future reference.

The acceptance of movement contracts will depend largely on how little effort is involved in specifying the intended movement. For example, a simple high-level description might be "at 8.00h I'll take the car from my home to the office via the motorway A5 as usual". Ideally, a software agent on the mobile terminal relieves the user of this task by inferring his intentions from the context and only having him confirm the results. Ultimately, however, this high-level description needs to be translated into a set of visited cells and arrival/departure estimates for each cell, which can be used for improving resource management. This is done in a two-stage process:

1) First, the mobile terminal translates the high-level description into a neutral format, using geographical coordinates to describe the spatial aspects and mathematical expressions to describe the temporal aspects of the user's movement during a particular session. This movement specification consists of a small number of parameters and is passed to the network during contract negotiation.
2) The network can then directly exploit this specification to estimate when each cell will be visited by the user. Due to the neutral intermediate format it does not need to have a notion of streets, transportation, etc., just as the mobile terminal does not require knowledge about the locations of the mobile network cells.

For the translation of the high-level description into the movement specification the route of the intended trip is determined and the trip is partitioned into segments with relatively homogeneous movement characteristics, distinguishing by transportation mode (car, bus, train, ...) and by street type (residential area street, highway), for example. The necessary information can be retrieved from car navigation systems, geographical databases, etc. and can be refined and individualized through data from previous trips taken by the user. In a second step, the network has to translate the movement specification into a set of visited cells and estimated arrival and departure times for each cell. This process is very lightweight, as the mapping of geographical regions to cells is a standard functionality of UMTS and cdma2000 networks [11], and the estimations can be done with a simple calculation based on the movement specification.

In the following sections we focus on how to specify movement using a small set of parameters. Following a more detailed description of two potential specification approaches, we also show how these specifications can be instantiated based on data sampled during previous trips.

B. Movement Specification

In a movement contract the network agrees to provide the mobile user with a certain service guarantee, provided that the user meets his self-imposed movement specification. Therefore, it is necessary that the network can derive the worst case movement behavior from this specification, i.e. the earliest arrival and the latest departure times for each cell. In order to allow for efficient resource management, these movement limits need to be as tight as possible. On the other hand, we want the movement specification to tolerate the typical daily variance in a user's movement behavior, for example to account for unexpected stops or slow phases caused by traffic lights or traffic jams, respectively. However, the movement specification cannot and is not intended to cover pathological cases—such as canceled trains due to strikes, for example—as this would result in extreme resource usage.

Still, the movement patterns of a mobile user can become arbitrarily complex. Suppose a user on his way from home to work, driving his car through a residential area first, then over the empty motorway into the crowded city center, there hopping onto the bus to his office. Each of these trip segments has very different movement characteristics with respect to the flexibility of the route taken, the minimum and maximum speeds, the number of stops, etc. Within a single segment, however, the movement displays relatively homogeneous characteristics. Therefore, it is reasonable to break a trip down into smaller segments that are easier to manage. The next step is to specify the spatial and temporal aspects of the movement within a single segment, i.e. to describe the geographical path taken by the user and at which point in time he will arrive at a given location. The complete movement specification is then the concatenation of all segments' spatial and temporal specifications.

a) Temporal Specification: As the contract guarantees availability of resources during the whole sojourn interval of a mobile user in a given cell, it is necessary that the temporal specification allows an access router to compute the earliest arrival time and the latest departure time of a user rather than the expected arrival or departure times. A very naïve approach is to specify the minimum and maximum speeds the user is allowed to travel in each trip segment to meet the specification. However, it is obvious that due to the unavoidable stops in city traffic the minimum speed would usually have to be zero and the maximum value would rather be a peak value that will rarely be met during a trip. Apart from this, the range between the earliest and latest arrival time at a given distance from the start of a trip segment would increase dramatically, leading to very inefficient resource allocations. It also does not capture the difference between the movement of a pedestrian, which is comparatively slow but constant, and a bus that is fast but has to stop frequently.

Rather than specifying bounds on a user's speed, we therefore use boundary functions for the traveled distance at a given point in time with respect to the origin of the trip. Let $v(t)$ be the mobile user's speed at time t. We say that a user meets

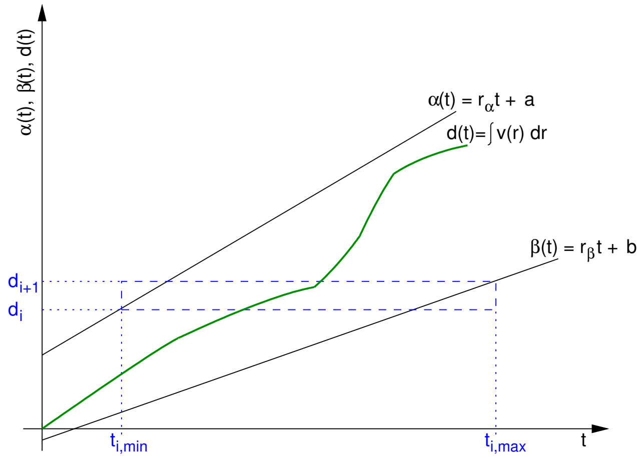

Fig. 1. Boundaries of Static Movement Specification

the temporal movement specification if

$$\forall t \geq 0: \quad \beta(t) \leq \underbrace{\int_0^t v(\tau)\, d\tau}_{=d(t)} \leq \alpha(t) \tag{1}$$

with $\alpha(t)$ and $\beta(t)$ being the upper and lower boundary functions, respectively. While in general the boundary functions could be arbitrarily close approximations of $d(t)$, we consider linear boundary functions, i.e. we set $\alpha(t) = r_\alpha t + a$ and $\beta(t) = r_\beta t + b$ with $r_\alpha \geq r_\beta \geq 0$, $a > 0$, $b \leq 0$ and $t \geq 0$. A real-world interpretation is that the user can move slower or faster, stop for a short period or even back up while still meeting the specification, as long as he does not cross the bounds given by two hypothetical users that move at a constant speed r_α with a head start of a and a constant speed r_β with a lag of b, respectively (see Figure 1).

Suppose now that a mobile terminal passes through a number of cells, entering a cell c_i at the distance d_i from the origin of the trip and leaving it upon entering the next cell at d_{i+1}. The time interval $[t_{i,min}, t_{i,max}]$ in which resources need to be reserved for it in cell c_i can then be calculated as

$$[t_{i,min}, t_{i,max}] = \left[\frac{[d_i - a]^+}{r_\alpha}, \frac{d_{i+1} - b}{r_\beta} \right] \tag{2}$$

where

$$[x]^+ = \begin{cases} x & x \geq 0 \\ 0 & \text{x} < 0 \end{cases}$$

While this specification does not permit movement faster than r_α over an extended period of time, for a short period the mobile terminal could move at arbitrarily high speeds. The reservation interval can be reduced further by adding minimum and maximum speeds v_{min} and v_{max} to the specification, so that for a given point in time τ we obtain

$$t_{i,min}(\tau) = \max\left\{\frac{[d_i - a]^+}{r_\alpha}, \frac{d_i - d(\tau)}{v_{max}} + \tau\right\}, \quad d(\tau) \le d_i \quad (3)$$

$$t_{i,max}(\tau) = \min\left\{\frac{d_{i+1} - b}{r_\beta}, \frac{d_{i+1} - d(\tau)}{v_{min}} + \tau\right\}, \quad d(\tau) \le d_{i+1} \quad (4)$$

In an implementation that uses this extended specification, the initial reservation windows are calculated upon receiving the specification and updated periodically at $t_n = nT, \ n = 0, \ldots, N$ where $N = \left\lfloor \frac{T_S}{T} \right\rfloor$, T is the update period, and T_S is the duration of the session.

Apart from the previous temporal specification with static boundaries, we also propose a specification that adapts the speed of the hypothetical users so that they always remain within a certain distance of the user. For this specification we assume that the user gets continually closer to his destination, so that $d(t)$ is a wide-sense increasing function, i.e. $d(t_1) \le d(t_2)$ for all $t_1 \le t_2$. The user meets the temporal specification if

$$\begin{aligned} \forall t \ge 0 : \ & \beta(t - s) \le d(t) \le \alpha(t - s) \\ & \forall\, s \in \{t_n \mid n = \{0, \ldots, N\} \wedge t_n \le t\} \\ & \text{with } \alpha(0) = \beta(0) = 0 \end{aligned} \quad (5)$$

In contrast to the static specification, $d(t)$ is now not solely limited by the original boundary functions, but by the minimum (resp. maximum) of the set of curves that results when $\alpha(t)$ (resp. $\beta(t)$) is shifted along $d(t)$ for every t_n (see Figure 2). The resulting boundary curves can be computed for each point in time τ using a discrete version of the min-plus (resp. max-plus) convolution[12]:

$$\begin{aligned} u_\tau(t) &= d(t) \underline{\otimes} \alpha(t) \\ &= \min_{n \in \left\{0, \ldots, \left\lfloor \frac{\tau}{T} \right\rfloor\right\} : t_n \le t} \{d(t_n) + \alpha(t - t_n)\} \quad (6) \\ l_\tau(t) &= d(t) \overline{\otimes} \beta(t) \\ &= \max_{n \in \left\{0, \ldots, \left\lfloor \frac{\tau}{T} \right\rfloor\right\} : t_n \le t} \{d(t_n) + \beta(t - t_n)\} \quad (7) \end{aligned}$$

This results in a much stricter specification than before (see again Figure 2: the size of the reservation window is now considerably smaller). The worst case estimate for the reservation interval can be derived using the pseudo-inverses of $u_\tau(t)$ and $l_\tau(t)$, which are defined as $u_\tau^{-1}(d) = \inf\{t \ge 0 \wedge u_\tau(t) = d, \ d \in \mathbb{R}^+\}$ and $l_\tau^{-1}(d) = \sup\{t \ge 0 \wedge l_\tau(t) = d, \ d \in \mathbb{R}^+\}$, respectively. In particular, for cell c_i we obtain

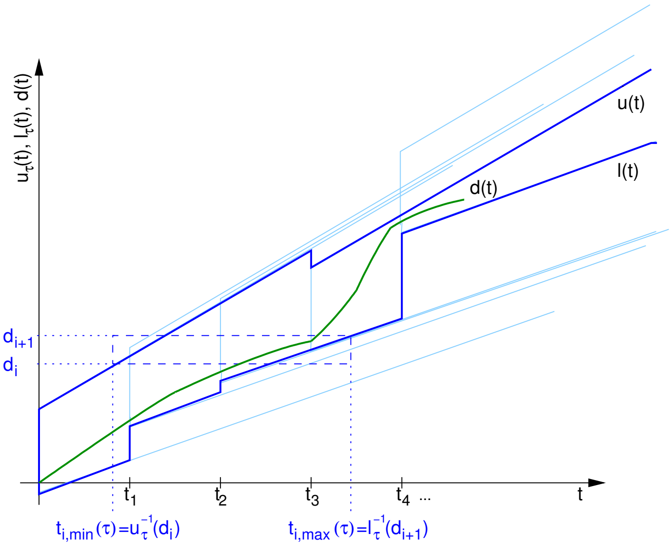

Fig. 2. Boundaries of Dynamic Movement Specification

$$\begin{aligned} t_{i,min}(\tau) &= u_\tau^{-1}(d_i) \\ &= \inf\{t \ge 0 \wedge u_\tau(t) = d_i\} \\ &= \sup_{0 \le s \le \tau} \left\{\frac{[d_i - d(s) - a]^+}{r_\alpha} + s\right\}, \ d(\tau) \le d_i \end{aligned} \quad (8)$$

$$\begin{aligned} t_{i,max}(\tau) &= l_\tau^{-1}(d_{i+1}) \\ &= \sup\{t \ge 0 \wedge l_\tau(t) = d_{i+1}\} \\ &= \inf_{0 \le s \le \tau} \left\{\frac{d_{i+1} - d(s) - b}{r_\beta} + s\right\}, \ d(\tau) \le d_{i+1} \end{aligned} \quad (9)$$

As in the first specification method, we use linear boundary functions $\alpha(t) = r_\alpha t + a$ and $\beta(t) = r_\beta t + b$. Again, this specification can be extended to include a minimum and a maximum permitted speed. This results in four different temporal movement specifications: the static boundaries with no speed limitation (sbns), dynamic boundaries with no speed limitation (dbns), and the respective versions with speed limit (sbs and dbs). Note that all specifications describe the temporal aspects of movement using only four and six parameters, respectively.

b) Spatial Specification: Using one of the temporal specifications from above, the network can determine the time interval in which a user will have reached a given distance from the origin of his trip. To calculate the resource reservation intervals in each cell, it further needs to know the path taken by the user, so that the visited cells and the traveled distance upon entering and leaving a cell can be determined.

A straightforward approach to define the path is to describe it as a series of vectors between geographical locations on the map. The distance from the origin $d(t)$ used in the temporal specification is measured along this path. To allow for some deviation from the ideal path—for small detours or because the path is not exactly known—an additional parameter per vector describes the width of the permitted area around the vector, so that the spatial specification is effectively a corridor consisting of a series of rectangular geographic regions.

C. Parameter Fitting

This section will briefly describe some possible approaches to find the parameters for a movement specification. The spatial specification requires information about the path between the origin and the destination of a trip, which can, for example, be retrieved from car navigation systems or from data of previous trips. The number of corridor elements and their widths will depend on the accuracy of the available information.

Likewise, the initial parameters for the temporal specification can be taken from data of navigation systems, which store the speed limit and the type of each road, i.e. whether it is a motorway, residential area road, etc. This data can afterwards be refined and personalized, especially through historical data from previous trips.

The simulations described below derive the movement specification for a trip from time-distance-samples taken during only three previous repetitions of the same trip unless otherwise noted. Note that a larger number of trips could be used to give the movement specification higher accuracy. Two different algorithms were used to find the parameters. The first one uses a standard linear regression to find a trend line for the samples and then shifts the trend line up and down the time axis of a time-distance-diagram until it becomes an upper and lower boundary line, respectively. The other algorithm chooses boundary lines through two points on the convex hull of the sample set, such that the area between the two boundary lines is minimized.

III. Simulations

A. Environment and Setup

The quality of the proposed movement specifications—how well they can describe a mobile user's movement in advance—has been evaluated through simulations of a mobile user's movement through a 17-by-17 grid of 500m long streets of three different types: residential area streets (maximum speed of 8m/s), inner-city streets (14m/s), and highways (28m/s).

Since existing mobility models (such as the popular "random waypoint" [13], for example) usually use constant or piece-wise constant node speeds, they lack the temporal complexity required for meaningful evaluations of movement specifications. Instead, we used a mobility model in which nodes always try to accelerate continuously to the maximum speed allowed (resp. brake to the speed limit) on the edge they currently travel on by default, slowing down for turns. This free movement can then be impeded in two ways. At the end of each edge there is a traffic light at which the node has to brake and stop with a probability that depends on whether it needs to turn at this corner or not. We assume a red-light probability of 0.3 if it needs to turn and 0.15 if not, to account for the fact that traffic lights are usually programmed to impede the traffic that continues straight ahead as little as possible. After a stop, the user has to wait for a random (uniformly distributed) period of up to 60 seconds before continuing his trip. Furthermore, the user encounters traffic jams at random times (Poisson distributed with mean 500s), during which he has to slow down to a randomly chosen low speed during the duration of the jam (exponentially distributed with mean 20s)[1].

During a simulation, a single user has to make a number of 1000 trips between randomly chosen origins and destinations on the grid intersections. Each of these trips is repeated four times under varying traffic conditions. The first three repetitions are sampled to calculate the parameters for a movement specification. During the fourth repetition the movement specification is then applied, and the time that the user complies to it is compared to the total length of the trip. The path taken between the origin and destination of a trip is always the fastest path under normal traffic conditions.

B. Simulation Results

1) Specification Accuracy: In the first set of simulations the temporal movement specification with static boundary lines and that with dynamic boundary lines were evaluated with parameters from both the linear regression-based algorithm (regr) and the area minimizing algorithm (min). As Figure 3 shows, the specification with static boundary lines correctly describes 90% and more of the movement during short trips, with slowly decreasing performance as the trip becomes longer and more unexpected stops occur. The specification with dynamic boundaries displays poor accuracy at the beginning and improves with longer trips, but still remains inferior to the static specification. An analysis of this behavior showed that the parameters produced by the regression-based algorithm and especially by the more restrictive area minimizing algorithm are too conservative, especially at the beginning of a trip, so that already very slight variations of the movement lead to non-conformance to the temporal specification for the dynamic boundaries. As the algorithms for the parameter fitting have been tailored towards the static boundary specification, the accuracy of the dynamic boundary specification leaves room for significant improvement. The modified movement specifications that additionally included minimum and maximum speeds showed slightly, though not significantly, lower accuracy than their respective counterparts[2].

2) Sensitivity to Number of Sampled Trip Iterations: The quality of the movement specification also depends on the number of trip iterations used in determining the temporal specification parameters. In Figure 4, this number has been varied between one and ten iterations for trips of different lengths (1km and 4km) and using the static boundary specification (sbns). It shows that the movement specification benefits from each additional trip iteration, reaching 90% conformance

[1] These parameters were chosen arbitrarily. However, preliminary experiments showed that the results are not sensitive to these parameters even if they are varied over a wide range.

[2] For the sake of legibility their results have not been included in the figure.

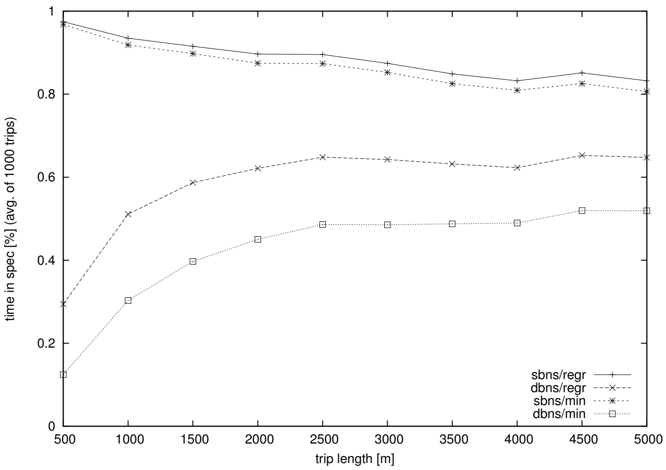

Fig. 3. Performance of Movement Specifications

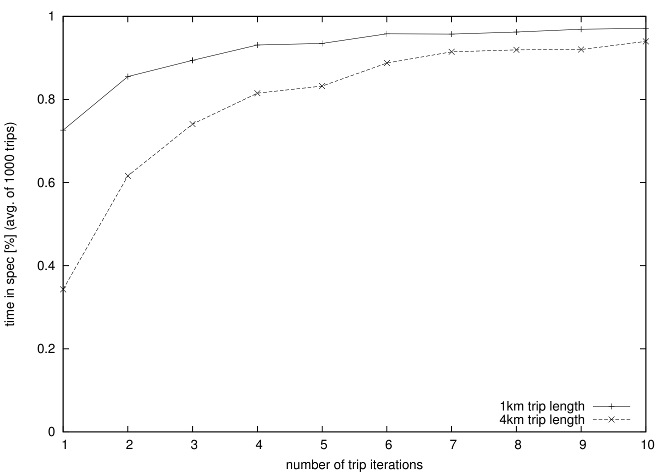

Fig. 4. Number of Sampled Trip Iterations

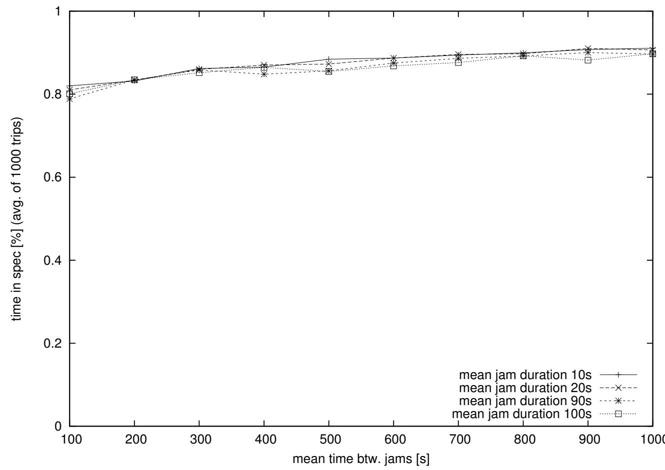

Fig. 5. Sensitivity to Traffic Jams

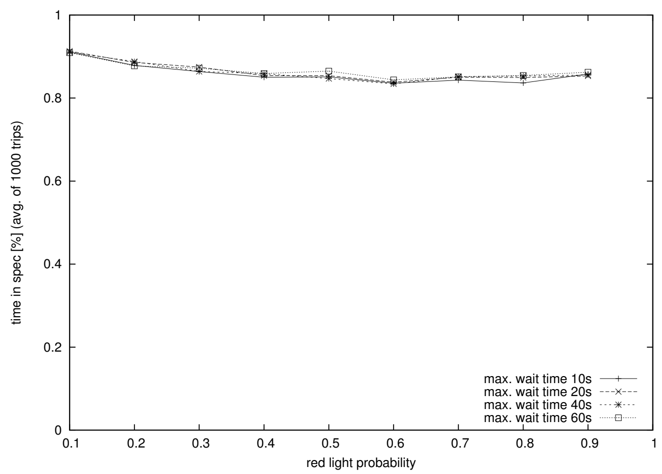

Fig. 6. Sensitivity to Traffic Lights

already after 4 and 7 iterations, respectively. With even more available history information the specification quality improves further, though less strongly.

3) Sensitivity to Impediments such as Traffic Jams and Red Lights: Furthermore, the specification should be robust against impediments due to traffic jams and red lights. As Figures 5 and 6 show, the specification quality decreases slightly when the rate of impediments increases, but is only slightly affected by the duration of the impediment, as it adapts to these changes. Of course, longer impediments still mean higher resource consumption.

4) Effect on Handover Dropping and Session Blocking: To evaluate the effect of movement specifications on handover dropping, we used a very simple resource management strategy that makes reservations based on the estimated sojourn times for each cell only once prior to the start of a session without updating them later. More sophisticated resource management strategies would delay reservations for distant cells and dynamically adapt existing reservations during a session as more accurate estimations become available. We then simulated trips of users in networks of different background loads[3].

We found that blocking and handover dropping probabilities are significantly reduced compared to best-effort and standard guard channel approaches even for moderate traffic loads (see Figures 7 and 8). Compared to best-effort, the guard channel manages to improve the handover dropping probability at the cost of an increased session blocking probability. When the network load is high, the majority of sessions that have not been blocked immediately are dropped later on during handovers. In sharp contrast, the movement contract is able to reduce the session blocking probability and the handover dropping probability at the same time even under high network loads, with a moderate additional effort for resource management.

[3]The background load of each cell was modeled as a Poisson arrival process with exponentially distributed session durations and offered loads of 20%, 40%, 60%, and 80%, respectively.

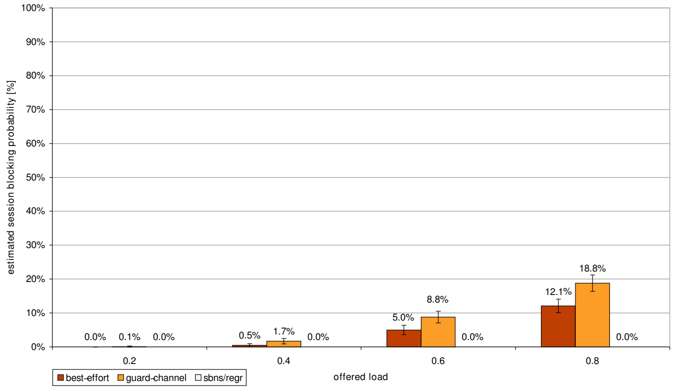

Fig. 7. Session Blocks

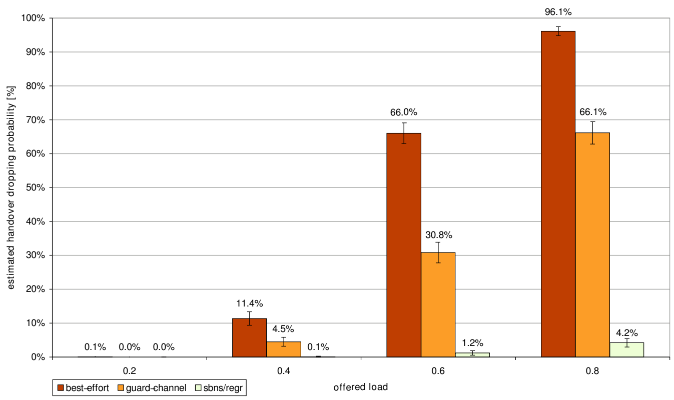

Fig. 8. Handover Drops

IV. Conclusion and Future Work

In this paper, we introduced the concept of a movement contract, which is a commitment of the network to provide a high QoS with respect to the handover dropping probability to a mobile user in return for receiving a specification of his expected movement during a session. We have described how the spatial and temporal aspects of user movement can be specified, contributing two temporal descriptions that require only a small set of parameters, and two algorithms to extract these parameters from past movement information.

Based on simulation results, we have shown that these movement specifications can describe movement including its typical daily variance due to stops and high traffic reasonably well. The parameters for the movement specifications can be derived from historical movement data of a small number of previous trips. Reservations based on these specifications can lead to a significant reduction of both call blocking and handover dropping simultaneously.

We plan to increase the quality of the movement specifications further by improving the parameter fitting algorithms, making them more appropriate especially for the temporal specification with dynamic boundaries. Furthermore, we would like to explore the use of more optimistic resource management strategies that better exploit the information from movement specifications.

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