Performance Analysis of the Distance-Based Location Update Mechanism of CDMA 1X EV-DO

Vijay Raman and Suresh Kalyanasundaram
Motorola India Electronics Limited
Bagmane Tech Park, C. V. Raman Nagar
Bangalore 560 093, India
E-mail: {vijayraman, Suresh.Kalyanasundaram}@motorola.com

Abstract

In this paper, we investigate the distance-based location update approach of CDMA 1X EV-DO's route update protocol. We develop an analytical model to compare its performance with that of the static location update approach of earlier cellular technologies. We show that, for the same paging delay and cost, the distance-based approach reduces the overhead traffic due to location update messages. In addition, this reduced loading is equally shared among all cells in the distance-based approach, while it is confined to the border cells in the static approach. We also introduce the non-uniform neighbor choice approach to model mobility more accurately and study its impact on the performance of the two algorithms. Using simulations we study a different mobility model, and the simulation results confirm the benefits of the distance-based approach of 1X EV-DO.

Keywords: location update, static; location update, distance-based; paging; CDMA 1X EV-DO; Markov chain;

1 Introduction

The trade-off between location update and paging in cellular systems is a well-researched topic [1, 2, 3, 4]. Reference [5] gives a comprehensive survey of the different location update mechanisms. Cellular systems employ a mobility management mechanism such that, when in idle mode, the network knows the location of the mobile at a coarser granularity than the cell level. In other words, the network does not track the location of an idle-mode mobile as it moves from cell to cell, but tracks it at a location-area level. A set of contiguous cells are grouped together into a location area, and the network knows the location of the mobile only to the granularity of location areas. (Different cellular technologies use different terms to refer to "location area." We will however use the term location area to refer to all such technology-specific terms.) Tracking mobiles at the location-area level (as opposed to the cell level) avoids excessive location update messages from the mobile. However, it increases the paging costs when there is an incoming call for the mobile. The network, since it knows only the current location area of the mobile, would have to page in all the cells within that location area. The network can employ smart paging strategies that progressively expand the search from the cell from which the mobile last sent a message to the network i.e., from the cell in which the network last received a location update message or from which the mobile ended its last call, whichever is most recent [6].

Most cellular systems employ a static location area concept, where a group of cells are designated as a location area and assigned a location area identifier (ID). Such a static location area concept has been used in GSM/GPRS/UMTS networks [7] and in IS-95 and CDMA-1X networks. Under this scheme, each cell broadcasts the ID of the location area of which it is a part. As idle-mode mobiles move from cell to cell, they monitor the location area ID and send back a location area update message if they move into a new location area. Location areas should be appropriately planned so that it reflects the trade-off between paging costs and location area update costs [8].

There are two primary disadvantages with the static location area approach. The first one is that mobiles "ping-ponging" between two cells that are on two different location areas generate unnecessary location area update messages although the distance they have traversed is not significant [9]. Another disadvantage is that the location update messages are not distributed evenly across cells. The location update traffic is confined to the cells that are on the boundary between two or more location areas. Because the resources for carrying the location update traffic also comes from the available pool of resources in a cell, uneven distribution of location update traffic results in unfairness and reduced capacity for carrying bearer traffic in the boundary cells.

To overcome the disadvantages of the static scheme, three kinds of dynamic schemes have been studied in the literature [1, 8]. These are timer-based, movement-based, and distance-based location update approaches. In the timer-based approach, each mobile sends a location update message after a fixed duration of time elapses. In the movement-based approach, once the number of cell crossings by a mobile exceeds a threshold, it sends a location update message. In the distance-based approach, the mobile sends a location update message whenever the distance between the current location of the mobile and its location when it last sent a location update message is greater than a threshold. Of these three dynamic approaches, the distance-based approach is more efficient, but also more complex [3]. Because the movement-based approach is seen as more practical to implement, most of the analyses have been for this mechanism, and for comparing the movement-based approach with the static approach [3, 8, 9]. However, as we describe below, CDMA 1X EV-DO has chosen the distance-based location update approach, and hence there is a need for a comprehensive analysis of the benefits of the distance-based approach over the static approach. We address this problem in this paper. Moreover, using the non-uniform neighbor choice approach, we introduce and study a new method to model mobility more accurately.

2 1X EV-DO Route Update Protocol

In CDMA 1X EV-DO, the idle-mode mobility management procedures are handled by the route update protocol, and it uses the distance-based location update approach [10]. In 1X EV-DO, each cell broadcasts its latitude, longitude, and a parameter called *RouteUpdateRadius*. An idle mode mobile, as it moves from cell to cell, monitors these three parameters. After each cell change, the mobile computes the distance between the site locations of the current cell and the cell in which it last sent a location update message. If this distance is greater than the *RouteUpdateRadius* parameter broadcast in the cell in which it last sent a location update message, the mobile sends another update to the network. Otherwise, the mobile does not send a location update message. To perform this operation, the mobile would have to store the latitude, longitude, and *RouteUpdateRadius* parameters of the last cell in which it did a location update operation. The distance computed is the distance between the site locations, and it does not depend on the location of the mobile within the serving site. The latitude and longitude information broadcast by each cell is used for computing this distance.

Because the mobile sends a location update message only after it moves to a cell that is sufficiently far apart from the cell from which the mobile last sent a location update, the problem of ping-ponging is eliminated. Essentially, as soon as a mobile sends a location update, it draws a circle around the serving cell of radius *RouteUpdateRadius* and sends the next location update only if it goes outside that circle. Clearly, this approach eliminates the ping-ponging problem of the static location area approach.

The problem of uneven loading of location update signaling messages is also eliminated with the 1X EV-DO distance-based location update mechanism. The randomness in the initial locations of mobiles, the cells in which their last calls got terminated, the cells in which they last sent a location update, and the *RouteUpdateRadius* ensure that there is uniform loading of location update messages across cells thus spreading this signaling load more evenly.

We develop an analytical model to compare the performance of the 1X EV-DO distance-based location update approach with that of the traditional static location area approach. The aggregate location update message load and the unfairness in the loading across cells are the two primary metrics we use to compare the two approaches. These metrics are computed while keeping the paging costs the same. We make the paging costs the same by configuring the *RouteUpdateRadius* such that the number of cells in which the mobile needs to be paged is identical in both the static approach and the distance-based location update approach.

3 Analytical Modeling

In this section, we model the mobility of users and solve for the mean time between location updates for the static location update strategy and the 1X EV-DO distance-based location update strategy. We assume that the time duration for which the mobile remains in a cell, called the cell residence time, is exponentially distributed with a mean of $1/\mu_{res}$ seconds. (We can relax this exponential assumption and allow the cell residence times to be any general distribution, in which case the continuous-time Markov chains will become semi-Markov chains. After uniformization, we will, however, get the same discrete-time embedded Markov chains as in the discussion that follows.) We consider two different cases for how the mobile chooses the next cell to visit. In the first case, the mobile chooses any of the neighbors of the current cell with equal probability. We deal with this case, which we call the random neighbor choice, in Section 3.1. The random choice of neighbors is obtained with $p = 0.5$ in Figure 1. In the second case, we model the behavior of mobiles to continue in the same direction. Here, the probability with which a mobile leaves the cell through any of the three faces opposite to the face through which it enters into the cell is $p/3$, where $0.5 \leq p \leq 1$. As illustrated in Figure 1, there is a higher probability (greater than 1/6) that the mobile leaves the cell through each of the three opposite faces. We handle this case, which we call non-uniform neighbor choice, in Section 3.2.

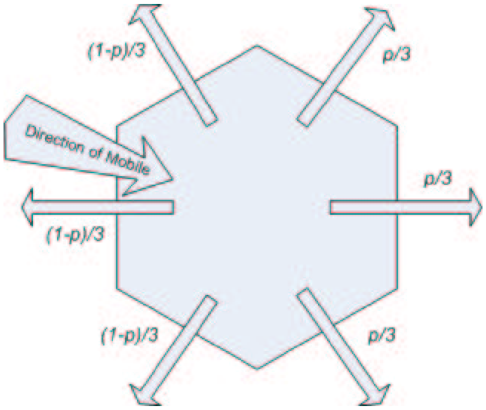

Figure 1: Probability with which the mobile leaves the different faces of the cell for the given direction of entry

3.1 Random Neighbor Choice

In this case, we assume that mobiles move to any of the current cell's neighbors with equal probability, i.e., with a probability of 1/6. Under these assumptions, both the location update strategies can be modeled as a finite-state absorbing Markov chain. (See Figure 2.)

We assume that the location area in the static location update method is such that the center cell along with a certain number of rings of neighbors together constitutes a location area. Although such location areas do not entirely tile the 2-D space, we still make the assumption to enable us to compare the performance of the two approaches. The state of a mobile is the ring index of the cell in which the mobile is currently camping. We denote the center cell as ring 0, and the first 6 neighbors around the center cell as ring 1, the next 12 neighbors as ring 2, and so on. It should be clear from the above description that the mobile can only make one step transitions, i.e., from state i, it can only go to state $i+1$ or $i-1$, provided such states exist. If we assume that the center cell along with d rings of neighbors constitutes a location area, then a transition from state d to the next ring away from the center would mean that a location update message would need to be sent by the mobile. We denote this as an "absorbing state," and we wish to determine the mean time a mobile takes to reach the absorbing state from the initial state. Note that once the mobile moves to the absorbing state, it essentially gets re-generated in the next location area in the initial state. The initial state in the static location update approach is state d, because the mobile enters the next location area in the d-th ring from the center cell.

In the 1X EV-DO approach, the mobile, as soon as it sends a location update message, essentially draws a circle around the centre of its new cell. Therefore, the initial state of a mobile in the distance-based approach is state 0. As in the static approach, we assume that the mobile sends a location update message when it goes beyond the d rings of neighbors around the cell from which it last sent a location update message. The number d is kept identical for both the methods to keep the paging costs the same. The objective is to compare the time between location update messages for the two schemes given that the paging costs are the same.

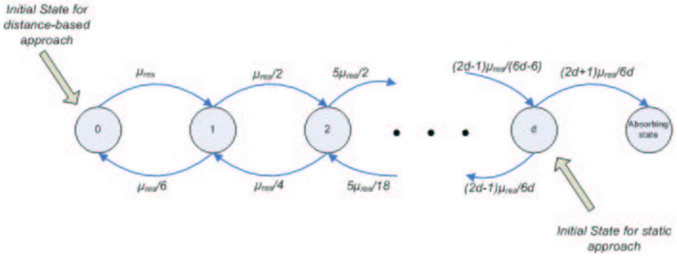

Figure 2: Continuous-time Markov chain for the static and distance-based location update approaches

The difference in the time between the location updates for these two schemes is due to the fact that the initial state for the distance-based approach is state 0, while for the static approach, it is state d. Intuitively, it should be clear from the Markov chain that the time to reach the absorbing state would be higher for the distance-based approach than for the static approach. It can be shown that the rate at which a mobile leaves state i for state $i-1$, if state $i-1$ exists, is given by $\mu_{res}(2i-1)/6i$ and similarly the rate at which a mobile leaves state i for state $i+1$ is $\mu_{res}(2i+1)/6i$, if state $i+1$ exists. The rate at which the mobile leaves state 0 for state 1 is μ_{res}. These expressions can be obtained by looking at the total number of edges of all hexagons in a given ring that takes the mobile to an inner ring and those that take it to an outer ring. For example, for the cells in ring 1, there are thirty six edges in all. Of these, six edges face the center cell in ring 0, twelve edges face cells in ring 1 itself, and eighteen edges face the cells in ring 2. By induction, we can show that for ring i, the number of edges that face ring $i-1$, ring i, and ring $i+1$ are in the ratio of $2i-1 : 2i : 2i+1$.

By using the uniformization technique, the above continuous-time Markov chain can be converted to a discrete-time version. See Figure 3. Note that the discrete-time version has transitions from a state to itself (except for state 0) to allow for movement of a mobile within the same ring. We can then obtain the number of cell residence times between two location area update messages from a mobile. We denote by T_i the average number of cell residence times for a mobile to reach the absorbing state from state i.

We can solve for T_i for all i using the following set of equations:

$$T_i = 1 + \sum_{j=i-1}^{i+1} p_{ij} T_j \tag{1}$$

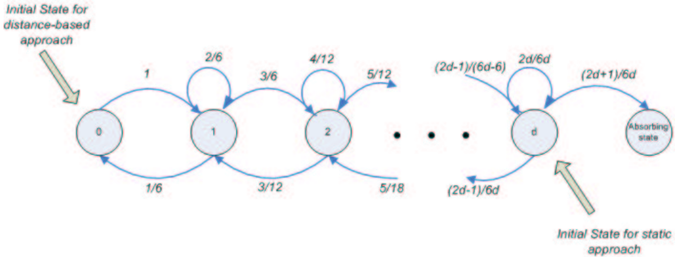

Figure 3: Discrete-time Markov chain after applying the uniformization technique for the static and distance-based location update approaches

Figure 4 compares the average number of cell residence times that elapse between two location update messages from the same mobile. We make this plot as a function of d, the number of rings of cells in a location area. We find that the time between updates for the distance-based approach is much larger than that of the static approach. This implies that the aggregate overhead traffic due to location update messages will be higher for the static approach when compared to the distance-based approach, for the same paging cost. Figure 4 also shows that, as we increase d, the average number of cell residence times between location updates increase, as expected. Although this increase happens for both the approaches, the increase is faster for the distance-based approach when compared to the static approach.

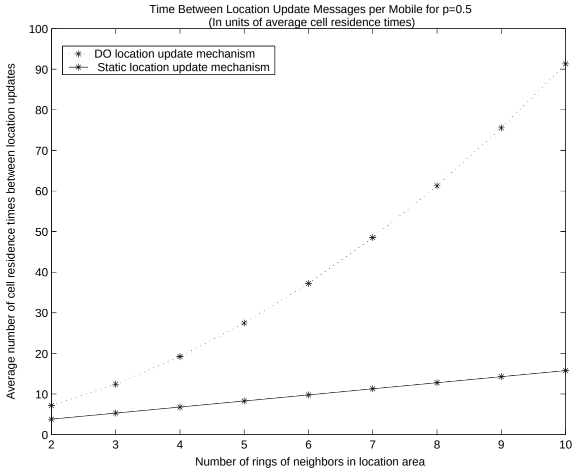

Figure 4: Average time between location updates (in units of average cell residence times) for distance-based and static location update approaches.

3.2 Non-uniform Neighbor Choice

In this case, the probability with which the mobile leaves through any of the three opposite faces is p, where $0.5 \leq p < 1.0$, and this probability is divided equally among the three faces. The sum of the probabilities with which the mobile leaves via the face it came into the cell or its nearest two neighbors is $1-p$, with this probability divided equally among these three faces. See Figure 1. We use this mechanism to model the effect that mobiles are more likely to move in a "forward" direction than in a "backward" direction. With this modification, the ring number of the mobile is no longer a Markov chain, because the next ring that the mobile will move into also depends on the ring from which the mobile came into the current cell. However, we will still get a Markov chain if we include the ring from which the mobile came into the current ring also as part of the state. We define three types of states:

- States of the form $i \leftarrow i-1$, which is used to denote that the mobile is currently in a cell in ring i and has moved to this cell from a cell in ring $i-1$.
- States of the form $i \leftarrow i+1$, which is used to denote that the mobile is currently in a cell in ring i, and has moved to this cell from a cell in ring $i+1$.
- States of the form $i \leftarrow i$, which is used to denote that the mobile is currently in a cell in ring i, and has moved into this cell from another cell in ring i.

Note that there are some exceptions to the above rules for states. Specifically, states $0 \leftarrow -1$ does not make sense because there is no ring -1. Similarly, state $0 \leftarrow 0$ does not make sense because if we leave the only cell in ring 0, we necessarily have to go to ring 1. Therefore, we denote the only relevant state when the mobile is in ring 0 as state 0. As before, we assume that when a mobile moves from a cell in ring d in a direction away from the center, it goes into the absorbing state, where it needs to send a location update message. Although there is no ring $d+1$, state $d \leftarrow d+1$ still is meaningful because this is the initial state of a mobile in the static location update mechanism. In the distance-based location update mechanism, the initial state is state 0. The resulting discrete-time Markov chain is shown in Figure 5.

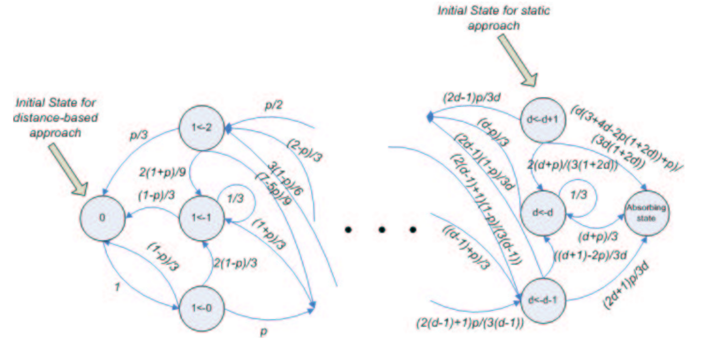

Figure 5: Discrete-time Markov chain for the static and distance-based approaches with non-uniform neighbor choice

In Figure 6 we show the transition probabilities for states of the form $i \leftarrow i+1$, $i \leftarrow i-1$, and $i \leftarrow i$. These probabilities have been obtained by looking at the number of faces from a certain ring i that look into cells in ring i, ring $i-1$, and ring $i+1$, with probabilities $p/3$ and $(1-p)/3$. For example, to compute the probability of remaining in state $i \leftarrow i$ we see that two out of six faces keep the mobile in the same state, and one of those will have a probability of $p/3$ and the other will have a probability of $(1-p)/3$ associated with it. The probability of $(1-p)/3$ will be associated with the face through which the mobile reached the cell, and the probability of $p/3$ will be associated with the face opposite to the one through which the mobile came into the cell. Thus the probability of the mobile remaining in state $i \leftarrow i$ is $1/3$. All the other transition probabilities can be computed by using some careful accounting. Using these transition probabilities, we can again solve for the mean duration to reach the absorbing state from each of the states by using Eq. (1), with the limits on the summation appropriately modified. The mean time between updates for the static location area update mechanism is given by $T_{d \leftarrow d+1}$ and that of the distance-based approach is given by T_0.

In Figure 7, we compare the effect of changing p on the average number of cell residence times before an update is made in the static and distance-based location update strategies. We find that, with increasing p, the distance-based location update strategy makes more frequent updates because mobiles continue to move in the same direction for longer. In the case of the static approach, however, the time between two location update messages increases marginally with increasing p. This is because, having come from ring $d+1$, the mobile is more likely go towards the center of the location area instead

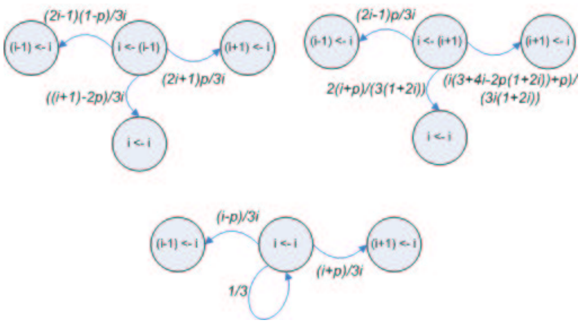

Figure 6: General equations for transition probabilities out of states $i \leftarrow (i-1)$, $i \leftarrow i$, and $i \leftarrow (i+1)$

of ping-ponging back into the location area from which it just entered. The impact of the value of p on the static location update approach can be seen more clearly in Figure 8. With $p = 0.5$, we obtain the curve we obtained in Figure 4, as expected. Thus we find that the distance-based location update mechanism continues to perform better than the static approach even under a very non-uniform neighbor choice model with $p = 0.8$. Note that we expect the mobility model to be close to the random neighbor choice model when the cell sizes are fairly large and when mobility is restricted. It is more likely to be non-uniform in highway-type cells, or with small cell sizes.

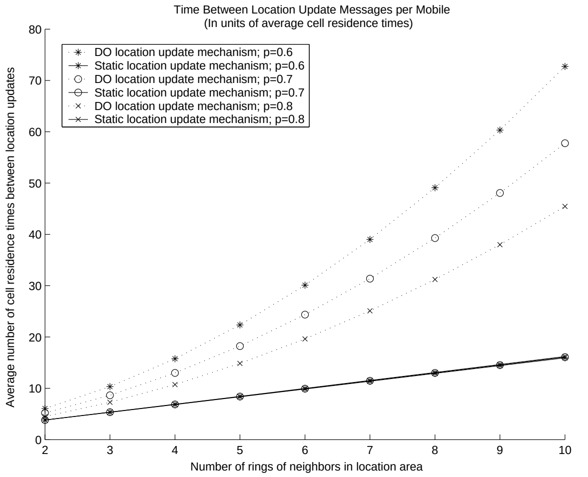

Figure 7: Average time between location updates (in units of average cell residence times) for distance-based and static location update approaches with non-uniform neighbor choice

These results show that the aggregate location update message loading is higher in the static approach when compared to the distance-based approach. In addition, this larger aggregate loading is shared among fewer cells in the static approach. In the distance-based approach, the location update loading is shared among all cells. Note that when there are d rings of neighbors around the center cell (which is assumed to be ring 0), the location update loading will be limited to $6d$ border cells for the static approach. For the distance-based approach, it will be shared among $1 + \sum_{i=1}^{d} 6i = 1 + 3d(d+1)$ cells that constitute the entire location area. Figure 9 shows the ratio of the average loading per cell of the cells that have location update traffic for the static approach to the average loading per cell for the distance-based approach. We can see that the loading on the border cells in the static approach can be as much as 30 times that of the average loading of cells in the distance-based approach.

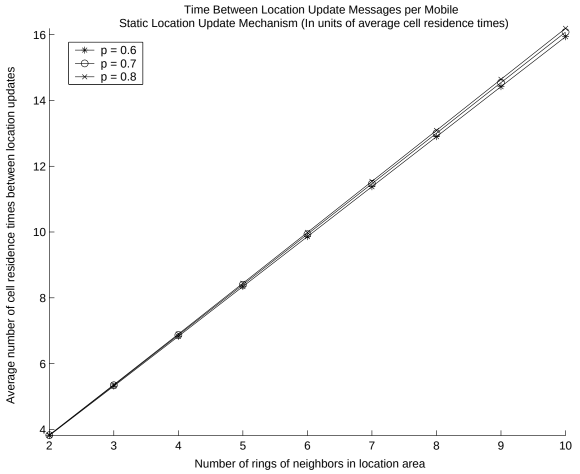

Figure 8: Average time between location updates (in units of average cell residence times) for static location update approach with non-uniform neighbor choice.

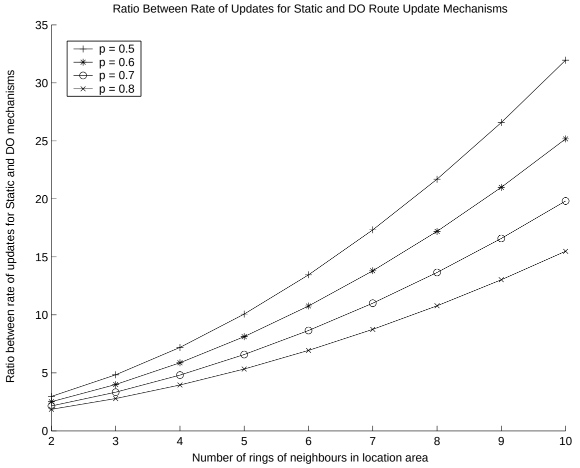

Figure 9: Ratio of location update loads for the static approach to that of the distance-based approach

4 Simulation Results

Using simulations, we also compare the performance of the two update mechanisms under other mobility scenarios. We simu-

Table 1: Average number of cell-residence times that elapse before a mobile sends a location update message

L (km), number of rings	Static approach	Distance-based approach
5, 2	3.08	5.24
15, 2	3.07	3.87
25, 2	3.08	3.63
5, 3	4.24	9.04
15, 3	4.28	5.72
25, 3	4.29	5.19

late nine square location areas with hexagonal cells, where the size of the hexagon is fixed at 1 km. We simulate scenarios similar to location areas having two and three rings of neighbors around the center cell by varying the side of the square location area appropriately. The length of this side is set such that the area of the square is equal to the sum of the areas of 19 cells for two rings of neighbors and 37 cells for three rings of neighbors. In the simulation model, mobiles choose a destination, and go towards the destination in a straight line. Once the destination is reached, it chooses another destination and moves towards that destination. The destination is chosen as follows: The direction of the destination is chosen uniformly in the range $(0, 2\pi)$, and the destination is chosen uniformly in the range $(0, L)$ km along the direction chosen. We consider values of 5, 15, and 25 km for L in our simulations. The speed with which the mobile moves towards the destination is chosen uniformly in the range $(0, 100)$ km/hr. The speed of the mobile is fixed until the destination is reached, but chosen randomly again for the mobility towards the next destination. We have a wrap-around model whereby mobiles that leave the simulation area come back into the area of interest from the opposite face. As in the analytical results, the metric of interest is the average number of cell residence times that elapse between two location area update messages from a mobile.

Table 1 shows the simulation results. We find that, for all values of L, the distance-based location update mechanism has lesser aggregate location update traffic. Increasing the value of L decreases the number of cell-residence times between updates for the distance-based approach. Increasing the value of L has an effect similar to increasing the value of p in the non-uniform neighbor choice approach, and, as expected from the analytical results, it increases the load due to location updates for the distance-based approach. Increasing the value of L has a very small impact on the static location update approach, which is also observed in the analytical results when the value of p is increased.

5 Conclusions

In this paper, we developed an analytical model to analyze the performance of the 1X EV-DO location update algorithm. The distance-based location update approach of 1X EV-DO was seen to perform better than the static approach of earlier cellular technologies. We found that the aggregate location update traffic is less for the distance-based approach than for the static approach, for the same paging cost. In addition, this loading is uniformly spread across all cells in the distance-based approach, while it is confined to the border cells alone in the static approach. We used the non-uniform neighbor choice approach to model more realistic mobility patterns. Simulation results with other mobility models also confirm the performance benefits of the distance-based approach of 1X EV-DO.

Acknowledgment

The authors would like to acknowledge useful discussion on the subject of this paper with Aniruddha Diwan, Srisankar Kunniyur, and Vinod Ramachandran.

References

[1] A. Bar Noy, I. Kessler, and M. Sidi, “Mobile Users: To Update or Not to Update,” *ACM-Baltzer Wireless Networks*, vol. 1, no. 2, pp. 187–196, 1994.

[2] J. S. M. Ho and I. F. Akyildiz, “Mobile User Location Update and Paging under Delay Constraints,” *ACM-Baltzer Wireless Networks*, vol. 1, no. 4, pp. 413–425, 1995.

[3] I. F. Akyildiz, J. S. M. Ho, and Y.-B. Lin, “Movement-Based Location Update and Selective Paging for PCS Networks,” *IEEE/ACM Transactions on Networking*, vol. 4, pp. 629–638, August 1996.

[4] P. G. Escalle, V. G. Giner, and J. M. Oltra, “Reducing Location Update and Paging Costs in a PCS Network,” *IEEE Transactions on Wireless Communications*, vol. 1, no. 1, pp. 200–209, January 2002.

[5] W. S. V. Wong and V. C. M. Leung, “Location Management for Next Generation Personal Communication Networks,” *IEEE Network*, vol. 14, no. 5, pp. 18–24, September/October 2000.

[6] C. Rose and R. Yates, “Minimizing the Average Cost of Paging under Delay Constraints,” *Wireless Networks*, vol. 1, pp. 211–219, 1995.

[7] 3GPP TS 23.060, “General Packet Radio Service: Service description; Stage 2,” Available from www.3gpp.org.

[8] J. Li, Y. Pan, and X. Jia, “Analysis of Dynamic Location Management for PCS Networks,” *IEEE Transactions on Vehicular Technology*, vol. 51, no. 5, pp. 1109–1119, September 2002.

[9] J. Li, H. Kameda, and K. Li, “Optimal Dynamic Mobility Management for PCS Networks,” *IEEE/ACM Transactions on Networking*, vol. 8, no. 3, pp. 319–327, June 2000.

[10] 3GPP2 C.S0024-A v1.0 “CDMA 2000 High Rate Packet Data Air Interface Specification,” Available from www.3gpp2.org.