Design and Analysis of a TDMA Call Assignment Scheme for Cellular Networks

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Abstract: In this paper, we introduce a multiple access scheme suited for use in packet switched personal communication services (PCS) networks is introduced. This scheme is called Handoff TDMA (H-TDMA). Under this scheme, three type of traffic, new voice calls, handoff voice calls and data packets, compete to use a number of free time slots called frames. The priority is given to voice calls over data packets while a number of slots is exclusively used by data packets. To avoid the undesirable situation in which a free slot in data packets partition remain idle while handoff or new calls requests rejected, a dynamic boundary concept is introduced. Given a binomial arrival distribution, we derive distribution of the number of new voice call , handoff calls and data packets. We evaluate the forced termination probability and the blocking probability, as well as the data packets loss probability. The numerical results indicate that the H-TDMA improve both the forced termination probability and data loss probability in both low and high MS.

Key–Words: CN networks, call holding time, channel assignment, handoff rate, forced termination, degradation time, Blocking probability.

1 Introduction

In cellular networks (CNs) [2, 3] a mobile phone, henceforth called mobile station (MS), can move freely from cell to cell. The phone is managed in each cell by the base station (BS) of that cell. If the MS is moving and a call is in progress, the call will be transferred (handoffed) each time a new cell is entered [5].

Each base station (BS) in a CN provides a fixed number of communications channels [2, 4] in a preallocated frequency bandwidth. Requests for new voice calls, handoff voice calls and data calls arrive at the BS of a cell competing for the free channels in that cell. This requires a careful channel assignment scheme [3, 6] that efficiently utilizes the scarce bandwidth used by the network [7].

In principle, handoff can be carried out for both types. However, in our model we will assume a system that has handoff only for voice calls. This assumption is realistic in view of the fact that data calls are typically messages so short that they can be completed at the same cell they are started. The duration of the call, no matter how many handoffs are made, is called the call holding time. The duration an MS stays in a given cell is called the cell residence time or dwell time.

Modern cellular networks, e.g. GSM, use Time-division multiple-access (TDMA). The idea of TDMA is to divide time into slots, with c time slots comprising a frame. A channel is basically a particular time slot that reoccurs every frame. Each frame is made up of a preamble, an information message, and tail bits. Various TDMA channel assignment schemes have been proposed and analyzed in the context of cellular networks.

In [8], an access scheme that combines TDMA multiplexing with an efficient reservation strategy for the dynamic allocation of slots within a frame is presented. The arrival process of both voice and data calls is assumed to be Bernoulli in each slot. However, no distinction is made in this paper between new and handoff voice calls.

In [9], the performance evaluation of a voice and data integration scheme has been carried out. However, voice and data calls in this work are considered independent of each other, and as a consequence, voice and data subsystems are analyzed separately.

In [10], a reservation TDMA scheme is presented. It provides integrated voice/data transmission in a cellular network. In this scheme, voice calls can use all the frame slots while data calls can use only the free slot. In other words, no resources are exclusively allocated to data calls, seriously threatening the quality of service for data calls.

In [11], two multiple channel access control schemes have been proposed and analyzed for integrating voice and data traffic in both medium and high capacity microcellular environments. Voice traffic is offered almost absolute priority over data traffic, due to its more stringent quality of service requirements. However, no distinction is made in this paper between new and handoff voice calls.

In [12], three TDMA channel assignment schemes are considered, namely Sequential Trunk Hunt (STH), Intelligent Channel Assignment (ICA), in the context of call packing/repacking. However, no distinction is made in this paper between new and handoff voice calls.

In the present paper, we propose a new handoff TDMA call assignment scheme for an integrated voice/data cellular network. This scheme differs from the above in the way it treats new and handoff voice calls, basically favoring the latter, and in the fact that it dedicates some channels for the exclusive use of data calls, in order to improve their quality of service. Details of how the scheme works are given in Section 2.

The performance of our scheme is analyzed using a Markovian queueing model. The analysis culminates with such important measures as the blocking probability, the forced termination probability, the system occupancy, the expected number of new and handoff voice calls and expected number of data calls. The analysis is carried out under the assumption that the cell residence time, the call degradation time and the call holding time have geometric distributions.

This paper is organized as follows. In section 2, the proposed scheme is presented. In section 3, the system occupancy is evaluated. In section 4, the blocking probability, expected number of voice calls, forced termination probability and data call loss probability are obtained. Some numerical results are presented in section 5 and conclusions are drawn in section 6.

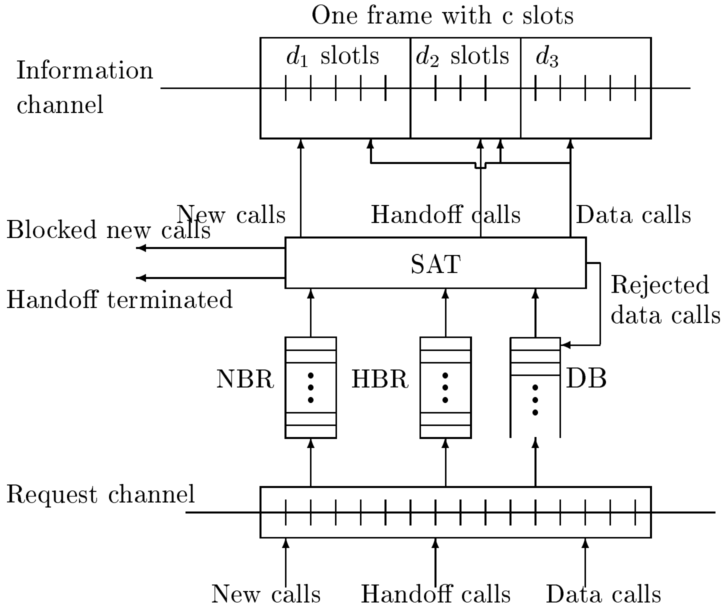

Figure 1: Channel assignment scheme

2 Model Assumptions

We consider a typical GSM cellular system that operates under the following assumptions.

1. That is, the time axis is divided into successive periods called frame. Each frame contains $c > 0$ slots, each equal to the transmission time of one packet.

2. The bandwidth is divided into two logical channels, the information channel, used for information packets, and request channel, used for request packets, as shown in Figure 1. These packets are either voice packets or data packets. The voice packets can either belong to a new call or a handoff call.

3. Information packets are of the same length, as are request packets, with the latter much shorter than the former.

4. As shown in Figure 1, the slots in each frame are divided into three partitions. Note that the slots in the each partition are in reality not necessarily contiguous, as might be inferred from the logical diagram in Figure 1. Partition 1 is of size $0 \leq d_1 \leq c_1$, with c_1 a predetermined nonzero maximum, and is dedicated to new calls. Partition 2 is of size $0 \leq d_2 \leq c_2$, with c_2 a predetermined nonzero maximum, and is dedicated to handoff calls.

Partition 3 is of size $c - c_1 - c_2 \leq d_3 \leq c$ and is dedicated to data. The value of d_3 at any time is given by

$$\begin{aligned} d_3 &= \max\left(c - c_1 - c_2, c - \min\left(c_1, i\right)\right. \\ &\quad \left. - \min\left(c_2, j\right)\right) \end{aligned}$$

where i and j are the current number of new and handoff calls respectively.

5. When a request packet arrives at the BS during frame k, its type will be investigated. New and handoff call requests are placed into the New Request Buffer (NRB) and Handoff Request Buffer (HRB), respectively. These two buffers are assumed to be large but finite. Data requests are not buffered, but their corresponding packets are placed into a Data Buffer (DB) whose size is L. The BS keeps a slot allocation table (SAT) to store information about the state of each slot (free or used) in frame k. At the end of the frame, the BS updates the SAT.

6. At the start of frame $k+1$, if there is a new call request, the BS tries to assign a slot within partition 1 to it. If such a slot is not available, the request is blocked.

7. Partition 2 is managed in the same way as partition 1 above, but here if the assignment fails, the handoff request is forcefully terminated.

8. As for partition 3, there are two cases. If the number of packets in the DB is less than or equal to $c - c_1 - c_2$, then all of them will be assigned slots in the frame. Else, $c - d_1 - d_2$ packets will be assigned slots and the remaining packets will have to attempt in the next frame.

9. The call holding time of new and handoff calls is geometrically distributed with parameters μ_v and μ_h, respectively.

10. The cell residence time is geometrically distributed with parameter μ_r.

11. By the end of each frame, an ongoing new call will leave the cell, either by being completed or by making a handoff to a neighbor cell, with probability $s_1 = \mu_v + \mu_r$ or will not leave with probability $\overline{s_1} = 1 - s_1$. In a similar way, an ongoing handoff call will leave the cell with probability $s_2 = \mu_h + \mu_r$ or will not leave with probability $\overline{s_2} = 1 - s_2$. Let D_1^k and D_2^k be two random variables (RVs) denoting the number of new calls and handoff calls leaving a cell at the end of frame k, respectively. Then D_1^k and D_2^k follow a binomial distribution with parameters d_1, s_1 and d_2, s_2, respectively.

12. The service time of each data packet is deterministic to one slot per frame. Let D_3^k denote the number of data packets that will leave a cell by the end of frame k.

13. The arrival of calls in each of the three types follows a binomial distribution. The parameters of this distribution are M_1, r_1 for new calls, M_2, r_2 for handoff calls, and M_3, r_3 for data calls. We shall assume that $M_1 \gg c_1$, $M_2 \gg c_2$, and $M_3 \gg \dot{c}$. Let $A_1^k = 0, 1, \cdots, M_1$, be RV denote the number of new calls that arrive at the BS during frame k. And let $A_2^k = 0, 1, \cdots, M_2$, denote the number of handoff calls that arrive at the BS during frame k. Also, let $A_3^k = 0, 1, \cdots, M_3$, denote the number of data calls that arrive at the BS during frame k. The three RVs A_1^k, A_2^k and A_3^k are assumed mutually independent. The RVs A_1^k are iid, and so are the RVs A_2^k and A_3^k. Then the common distribution of the $A_i^k, i = 1, 2, 3$, is

$$B\left(n; M_i, r_i\right) \triangleq \Pr\left[A_i = n\right] = \binom{M_i}{n} r_i^n \overline{r_i}^{M_i - n} \tag{1}$$

3 System Occupancy

In this section, we analyze the steady state cell occupancy, i.e. the number of new and handoff calls, as well as the number of data packets in the cell at the end of an arbitrary frame during steady state. For this propose, a detailed Markov model is established.

Let $P_1^k = 0, 1, \cdots, c_1$, be a RV denoting the new calls occupancy in frame k, i.e. the number of active new calls at the end of frame k. The number of new calls that are completed by the end of frame $k+1$, D_1^{k+1}, is dependent on P_1^k with the following conditional distribution:

$$\Pr\left[D_1^{k+1} = n \middle| P_1^k = i\right] = B\left(n; i, s_1\right), 0 \leq n \leq i \leq c_1 \tag{2}$$

Let $P_2^k = 0, 1, \cdots, c_2$, be a RV denoting the handoff calls occupancy in frame k. The number of handoff calls that are completed by the end of frame $k+1$, D_2^{k+1}, is dependent on P_2^k with the following conditional distribution:

$$\Pr\left[D_2^{k+1} = n \middle| P_2^k = i\right] = B\left(n; i, s_2\right), \, 0 \le n \le i \le c_2 \tag{3}$$

Finally, let $P_3^k = 0, 1, \cdots$, be a RV denoting the data packets occupancy in frame k, i.e. the number of data packets in the buffer at the end of frame k. Note that data calls in a frame are all completed by the end of the frame.

In the next subsections, we will embark on finding the distribution of the number of new, handoff and data packets in the system. We will follow a similar strategy to that used in [13].

3.1 Voice Calls

Since new voice calls are given higher priority over data calls in partition 1, the new voice call is independent of both handoff calls and data calls. Recall that the maximum number of voice call arrivals in the cell is M_1 and the maximum number of new voice calls that can be accommodated simultaneously is c_1 calls per frame. Let $p_{1_{i,j}}$ be the one-step transition probability from the state $P_1^k = i$ at the start of frame k to the state $P_1^{k+1} = j$ at the start of frame $k+1$. That is,

$$p_{1_{i,j}} = \Pr\left[P_1^{k+1} = j \mid P_1^k = i\right], \; 0 \le i \le c_1, \; 0 \le j \le c_1 \tag{4}$$

Let us define $\Pi^v = \left[\pi_0^v, \, \pi_1^v, \ldots, \, \pi_{c_1}^v\right]$ to be the steady-state probability distribution of P_1^k, where

$$\pi_i^v = \Pr\left[P_1 = i\right], \; 0 \le i \le c_1$$

The probability distribution Π^v must satisfy the following matrix equation

$$\Pi^v = \Pi^v Q^v \tag{5}$$

where Q^v is the transition probability matrix with elements $p_{1_{i,j}} = \Pr\left(j \mid i\right)$ and size $c_1 + 1\times$ $c_1 + 1$. That is,

$$Q^v = \begin{bmatrix} p_{1_{0,0}} & p_{1_{0,1}} & \cdots & p_{1_{0,c_1}} \\ p_{1_{1,0}} & p_{1_{1,1}} & \cdots & p_{1_{1,c_1}} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1_{c_1,0}} & p_{1_{c_1,1}} & \cdots & p_{1_{c_1,c_1}} \end{bmatrix}$$

The approach of solving the c_1 equations in c_1 unknowns was not taken because of the size of the transition matrix which can in practice be as large as 500x500. It such large sizes, roundoff errors would be dangerous, and computation time prohibitive. Instead, an iterative procedure [14] is used, which makes use of the fact that the steady-state probability distribution of a Markov chain may be expressed as

$$\Pi^v = \lim_{k\to\infty} \Pi_0^v Q_k^v$$

where Π_0^v is an arbitrary initial distribution. The iteration will stop when there is a sufficiently small change from one iteration to the next. In other words, the criterion

$$\left|\pi_{i_{k+1}}^v - \pi_{i_k}^v\right| < \kappa, \; 0 \le i \le c_1$$

where κ is the convergence threshold. $\kappa = 10^{-9}$ is adopted here.

Now, we will embark on obtaining the elements of matrix Q_k^v. The one-step transition probabilities $p_{1_{i,j}}$ $(0 \le i \le c_1, \; 0 \le j \le c_1)$ has two cases. First, for $i =$ 0, 1, … ,c_1 and $j =$ 0, 1, … ,$c_1 - 1$ we have

$$\begin{aligned} p_{1_{i,j}} &= \Pr\left[P_1^{k+1} = j \mid P_1^k = i\right] \\ &= \sum_{l=\max(0,i-j)}^{i} \Pr\left[A_1^{k+1} = l + j - i \mid P_1^k = i\right] \\ &\quad \times \Pr\left[D_1^{k+1} = l \mid P_1^k = i\right] \end{aligned} \tag{6}$$

Second, for $i =$ 0, 1, … ,c_1 and $j = c_1$ we have

$$\begin{aligned} p_{1_{i,c_1}} &= \Pr\left[P_1^{k+1} = j \mid P_1^k = i\right] \\ &= \sum_{m=c_1}^{M} \sum_{l=0}^{i} \Pr\left[A_1^{k+1} = l + m - i \mid P_1^k = i\right] \\ &\quad \times \Pr\left[D_1^{k+1} = l \mid P_1^k = i\right] \end{aligned} \tag{7}$$

Noting that A_1^{k+1} is independent of P_1^k, and substituting (2) into (6) and (7), the one-step transition probabilities $p_{1_{i,j}}$ are given in steady state as follows

$$p_{1_{i,j}} = \begin{cases} \displaystyle\sum_{l=\max(0,i-j)}^{i} B\left(l + j - i; M_1, r_1\right) B\left(l; i, s_1\right) \\ \hfill 0 \le i \le c_1, 0 \le j < c_1 \\ \displaystyle\sum_{m=c_1}^{M} \sum_{l=0}^{i} B\left(l + m - i; M_1, r_1\right) B\left(l; i, s_1\right) \\ \hfill 0 \le i \le c_1, \; j = c_1 \end{cases} \tag{8}$$

In a manner similar, the one-step transition probability $p_{2_{i,j}}$ for handoff calls can be found to be

$$p_{2_{ij}} = \begin{cases} \sum\limits_{l=\max(0,i-j)}^{i} B\left(l+j-i; M_2, r_2\right) B\left(l; i, s_2\right) \\ \qquad\qquad 0 \le i \le c_2, 0 \le j < c_2 \\ \\ \sum\limits_{m=c_2}^{M} \sum\limits_{l=0}^{i} B\left(l+m-i; M_2, r_2\right) B\left(l; i, s_2\right) \\ \qquad\qquad 0 \le i \le c_2,\ j = c_2 \end{cases} \tag{9}$$

3.2 Data Calls

Since the DB is assumed to be finite of size L, the size of the transition probability matrix is also finite with size $L + d_3$. Let $p_{3_{l,m|i,j}}$ be the one-step transition probability from the current state $P_3^k = l$ at the start of frame k to the next state $P_3^{k+1} = m$ at the start of frame $k+1$ conditioned on both P_1^{k+1} and P_2^{k+1}. That is,

$$p_{3_{l,m|i,j}} = \Pr\left[P_3^{k+1} = m \mid P_3^k = l, P_1^{k+!} = i, P_2^{k+1} = j\right]$$

Let us define $\Pi_{i,j} = \left[\pi_{0|i,j},\ \pi_{1|i,j}, \cdots,\ \pi_{L+d_3|i,j}\right]$ to be the steady-state probability of P_3^k, where

$$\pi_{l|i,j} = \Pr\left[P_3 = l \mid P_1 = i, P_2 = j\right],\ 0 \le l \le L + d_3$$

The probability distribution $\Pi_{i,j}$ must satisfy the following matrix equation

$$\Pi_{i,j} = \Pi_{i,j} Q_{i,j} \tag{10}$$

where $Q_{i,j}$ is the transition probability matrix with elements $p_{3_{l,m|i,j}} = \Pr\left[m \mid l, i, j\right]$ and size $d_3 + L + 1\times\ d_3 + L + 1$ given i and j. That is

$$Q_{i,j} = \begin{bmatrix} p_{3_{0,0|i,j}} & p_{3_{0,1|i,j}} & \cdots & p_{3_{0,d_3+L|i,j}} \\ p_{3_{1,0|i,j}} & p_{3_{1,1|i,j}} & \cdots & p_{3_{1,d_3+L|i,j}} \\ \vdots & \vdots & \ddots & \vdots \\ p_{3_{d_3+L,0|i,j}} & p_{3_{d_3+L,1|i,j}} & \cdots & p_{3_{d_3+L,d_3+L|i,j}} \end{bmatrix}$$

The approach of solving the $L + d_3 + 1$ equations in $L + d_3 + 1$ unknowns is not taken because of the size of the transition matrix . Instead, an iterative procedure is used, which makes use of the fact that the steady-state probability distribution of a Markov chain may be expressed as

$$\Pi_{i,j} = \lim_{k\to\infty} \Pi_{i,j}^0 Q_{i,j}^k$$

where $\Pi_{i,j}^0$ is an arbitrary initial distribution given i and j. The iteration will stop when there is sufficiently small change, from one iteration to the next, in the probability distribution using the following criterion:

$$\left|\pi_{l|i,j}^{k+1} - \pi_{l|i,j}^{k}\right| < 10^{-7}, \quad 0 \le l \le L + d_3$$

$\kappa = 10^{-7}$ is adopted here. The elements of matrix $Q_{i,j}$ is given as

$$p_{3_{l,m|i,j}} = \begin{cases} B\left(m; N, r_3\right), \\ \quad 0 \le l \le d_3, 0 \le m \le d_3 + l \\ \\ B\left(m - l + d_3; N, r_3\right), \\ d < l \le L + d_3, 0 < m \le L + d_3 \end{cases} \tag{11}$$

where $p_{3_{l,m|i,j}} = 0$ for $m - l + d_3 < 0$.

4 Performance Measures

In this section three performance measures will be analyzed: the blocking probability of new calls, the forced termination probability of handoff calls, and the loss probability of data calls. The blocking probability of new calls will be obtained as follows. Since new calls can use a maximum of c_1 slots in each frame, a new call will be blocked if c_1 slots in the frame are occupied with new calls. According to the proposed scheme and the probability distributions given in (8), the blocking probability, B, of new voice call can be expressed as $B = \pi_{c_1}^v$ and the forced termination probability, $\digamma$, of a handoff call is given by $\digamma = r_2 \pi_{c_2}^h$. Finally, the data packets loss probability $P_{3_{loss}}$is given as

$$P_{3_{loss}} = \sum\nolimits_{i=0}^{c_1} \sum\nolimits_{j=0}^{c_2} \pi_{d_3+L|i,j} \pi_i^v \pi_j^h \tag{12}$$

5 Numerical Results

To get a feel for the performance measures obtained above, we will consider an example cellular network. Numerical results for this network will be obtained and plotted in graphs for visual convenience. In this example, we assume that the number of slots per frame, $c = 20.$, size of DB $L = 5$, size of new call population $M_1 = 100$, size of handoff call population $M_2 = 600$, size of data packets population $M_3 = 50$, the new voice call and handoff call arrival rate $r_1 = 0.02$ and

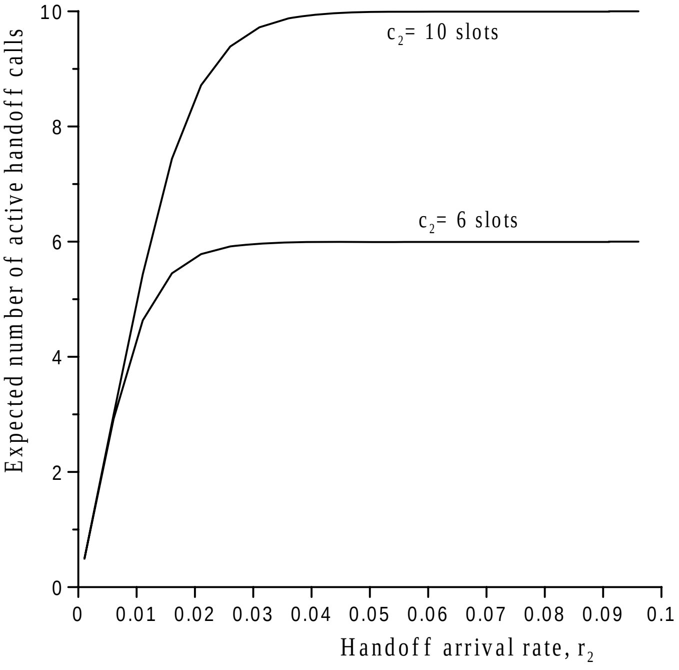

Figure 2: The expected number of handoffs vs the handoff arrival rate, r_2.

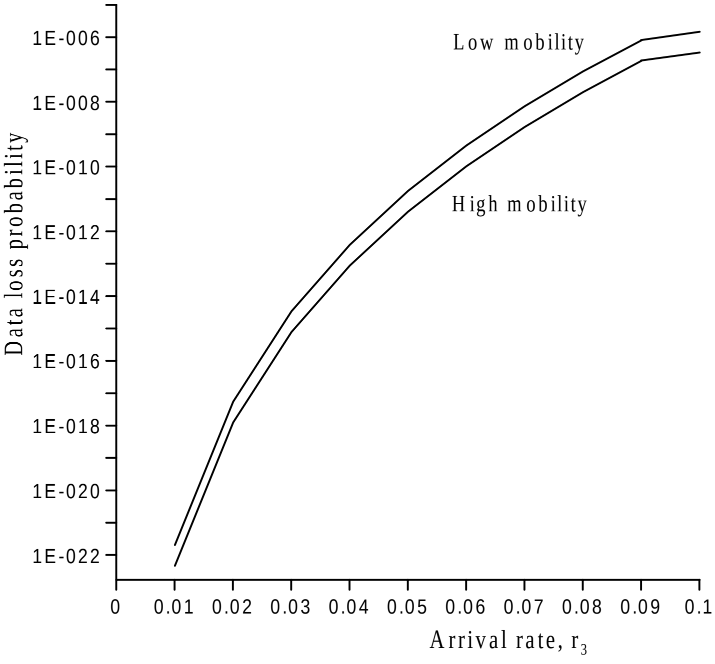

Figure 3: Data packets loss probability vs. data packet arrival rate.

$r_2 = 0.04$ respectively, and the holding time parameters are $\mu_h = \mu_v = 0.01 = 0.002$. As for the parameters μ_r and r_3, and the maxima c_1 and c_2, various values are assumed and shown directly on the respective graphs.

In Figure 2, the user mobility is fixed to 10. The Figure shows that the expected number of handoffs increases as the arrival rate of handoff voice call increases. The number increases almost linearly then saturates at a certain point. This phenomenon is due to the fact that as r_2 gets larger, slots of partition 2 become busier. This indicates that at high handoff traffic, the value of the threshold c_2 can be adjusted to decrease the handoff forced termination probability.

Figure 3 shows the data packets loss probability in both low and high MS mobility. The Figure shows that the data loss probability increases as the arrival rate of data packets increases, which is intuitively true. It also show that the loss probability increases in high mobility operating conditions. This phenomenon is due to the fact that high mobility results in an increase in the number of free slots shared by voice calls and data packets. This in turn leads to a decrease in the data queue length and hence a decrease in the data loss probability.

6 Conclusion

In this paper, a TDMA channel assignment scheme, with dynamic boundaries, for cellular networks is introduced and analyzed. The principal feature of the scheme is that it gives voice calls priority in getting channels over data calls and gives the latter exclusive access to a number of channels with non-preemptive power. The analysis, based on a Markov chain, is used to derive a system of linear equations. An iterative algorithm is provided to obtain the system steady-state solution. System performance measures, namely, the call forced termination probability, the data packets loss probability and the expected number of active voice calls, are obtained. The numerical results obtained for an example cellular network indicate that the scheme can be of practical value and can be used as an alternative to previously proposed channel assignment schemes.

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