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Mean Waiting Time Analysis in Finite Storage Queues for Wireless Cellular Networks

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Abstract. In this paper priority is assigned to the handover calls over new call attempts and blocked handover calls are placed in a finite storage queue. Total handover forced termination probability is evaluated and a suitable function for the mean service time at each position in the queue is theoretically estimated. Quality of service is obtained by introducing a threshold in the maximum waiting time of a handover call in the queue. In case the handover call mean service time at each queue position is found to be greater than this threshold, this call will be blocked. Simulation results show that this scheme provides satisfactory results for both types of calls.

Keywords: mobile communications systems, handover, waiting time, queuing of calls

1. Introduction

In case of microcellular networks where frequent handovers is a fact, Quality of Service (QoS) may degenerate below an acceptable level due to brief service interruptions. As the frequency of these interruption increases the perceived Qos is reduced. Also the chances of dropping a call due to factors such as the availability of channels increase with the number of handover attempts. All these issues place additional challenges on the design and dimensioning of microcellular wireless networks. Increasing the handoff rate, the probability of an ongoing call to be dropped due to a lack of free channel is high. This probability is also described as the probability of forced termination of handover calls P_F and it is a major criterion in performance evaluation of cellular systems.

Forced termination of an ongoing call is clearly less desirable than blocking of a new call attempt. Therefore, some channel assignment strategies with handover prioritization, guard channels [1], have been proposed in order to decrease the probability of forced termination. Hong and Rappaport [1] first proposed and analyzed a priority queuing model, according to which handover calls can be queued if all channels in the target cell are busy. If any channel is released while the mobile is in the handoff area, the first call in the queue occupies this channel. Infinite queue size is here considered. Chang et al. [5] later on proposed a two dimensional Markov chain queuing model for both types of calls, and in their model they also proved that it is not necessary to provide a very large queue size, thus a finite queuing is more suitable and realistic. Guerin [4] made also use of handover guard channels and new call queuing by proposing a two-dimensional Markov chain model. In his model, Guerin managed to find a closed-form solution for the state probabilities.

This paper is organized as follows: In Section 2, the mathematical analysis of the prioritized handover procedure is presented and the mean channel holding time is also empirically calculated using the model presented in [1]. In Section 3 we give the mathematical analysis of our proposed algorithm, giving priority to the handover calls over the new call attempts and also puts the blocked handover calls in a finite storage queue. The idea of the maximum waiting time in a queue is introduced, where a call should not wait in the queue for a long time before a free channel serves it, even if this call is still in the handoff area. Finally a mathematical expression for the new call and handover blocking probabilities is presented. Conclusions are provided in Section 4.

2. The Prioritized Handover Procedure

In order to study the handover queuing and present the impact of a queue on the system performance, it is necessary to analyze the prioritized handover procedure. The main aspects that have to be considered are (1) The mean channel holding time; (2) The cell radius; (3) The user mobility; (4) The mean call duration; (5) The guard channel reservation for handover calls.

The channel holding time T_H in a cell is defined as the time duration between the instant that a channel is occupied by a call and the instant it is released by either completion of the call or a cell boundary crossing by a portable, whichever is less. This time is a function of the cell radius R and of the maximum mobile velocity $V_{\max}$. We assume that the mean call duration T_M is the time an assigned channel would be held if no handoff is required and has an exponential distribution with mean value $\overline{T_M}(\equiv 1/\mu_M)$. The speed of a mobile in a cell is assumed to have a uniform distribution on the interval $[0, V_{\max}]$. The time for which a mobile resides in a cell to which the call is originated (is handed off) is denoted $T_n(T_h)$. The probability density functions of these holding times are [1]:

$$f_{Tn} = \frac{2V_{\max}}{\pi R^2}\sqrt{R^2 - \left(\frac{V_{\max}t}{2}\right)^2}, \quad 0 \le T \le \frac{2R}{V_{\max}} \tag{1}$$

$$f_{Th} = \frac{V_{\max}}{\pi\sqrt{R^2 - \left(\frac{V_{\max}t}{2}\right)^2}}, \quad 0 \le t \le \frac{2R}{V_{\max}} \tag{2}$$

The channel holding times of a new and handover call are given by:

$$T_{Hn} = \min(T_M, T_n)$$
$$T_{Hh} = \min(T_M, T_h).$$

Finally, it is proved [1] that the pdf of T_H is a function of the equations above and can be approximated to a negative exponential distribution with mean $\overline{T_H} = 1/\mu_H$. The value of μ_H can then be calculated using the following equation:

$$\int_0^\infty \left(F_{TH}^C(t) - e^{-\mu_H t}\right)dt = 0 \tag{3}$$

where F_{TH}^C is the complementary distribution function of the channel holding time.

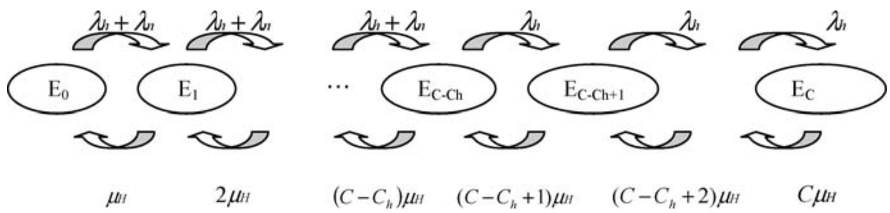

Figure 1. State-transition diagram for the prioritized handover procedure.

Priority can be given to handoff attempts by assigning C_h channels exclusively for handoff calls among the C channels in a cell. Both the new and the handoff calls can share the remaining $C - C_h$ channels. We define the state E_j of a cell such that there are j calls in progress and let P_j represent the steady-state probability to find this cell in state E_j. The probabilities can be determined by using a Markovian birth-death process in Figure 1.

Let λ_n and λ_h be the new calls and the handoff calls arrival rate, respectively. Denoting $\lambda = \lambda_h + \lambda_n$ as the total call arrival rate, then we can set

$$\lambda_h = a\lambda \tag{4}$$

The offered load ρ in a communication system is defined as

$$\rho = \frac{(\lambda_h + \lambda_n)}{\mu_H} \tag{5}$$

Using the steady-state equations from Figure 1, we conclude:

$$P_j = \begin{cases} \dfrac{\rho^j P_0}{j!}, & 0 \le j \le C - C_h \\ \dfrac{\rho^j P_0 a^{j-(C-C_h)}}{j!}, & C - C_h < j \le C \end{cases} \tag{6}$$

where P_0 denotes the probability of having 0 channels in use (calls in progress) and is derived by the total probability $\sum_{j=0}^{C} P_j = 1$. Thus

$$P_0 = \frac{1}{\sum_{j=0}^{C-C_h} \frac{\rho^j}{j!} + \sum_{j=C-C_h+1}^{C} \frac{\rho^j a^{j-(C-C_h)}}{j!}} \tag{7}$$

A new call will be blocked if it finds the system at a state greater than or equal to $C - C_h$:

$$P_B = \sum_{j=C-C_h}^{C} P_j \tag{8}$$

A handoff attempt will fail if the state number is equal to C, thus:

$$P_{fh} = P_C \tag{9}$$

3. Mathematical Analysis of the Proposed Handover Procedure

In this section we study a handover-prioritized procedure, according to which a handoff attempt may be queued if the state number in the cell is equal to C (All channels in the cell are busy). T_Q is the time that this attempt remains queued at a position q depends normally on whether or not a channel becomes available as long as the mobile is still in the handoff area. In this area, the average received power level by a mobile is between the handoff threshold level – initiation of the handover procedure – and the receiver threshold level [1]. A handoff attempt that joins the queue will be successful, if both of the following events occur before the mobile moves out of the handoff area:

(1) All of the attempts which joined the queue earlier than the given attempt have been disposed
(2) A channel becomes available when the given attempt is at the first position in the queue.

On the basis of our consideration, T_Q should have an upper bound. In order to have an effective system, a call must not be allowed to remain at a buffer position more than a maximum time threshold. Moreover, the queue size has to be limited because it is more realistic and practical than the infinite buffering. The maximum value of the mean service time $\overline{T_Q} = 1/\mu_Q$ is here obtained by the mean waiting time $\overline{W_h}$ in the queue.

The same analysis as in Section 2 is used and a similar Markovian birth-death process with k positions in the queue calculates the system steady-state probabilities in Figure 2.

Using the steady-state equations from Figure 2, we conclude:

$$P_j = \begin{cases} \dfrac{\rho^j}{j!} P_0, & 0 \le j \le C - C_h \\ \dfrac{\rho^j a^{j-(C-C_h)}}{j!} P_0, & C - C_h < j \le C \\ \dfrac{\rho^j a^{j-(C-C_h)}}{C! \prod_{i=1}^{j-C} (C\mu_H + i\mu_Q)} P_0, & C < j \le C + k \end{cases} \tag{10}$$

In the same way as in Section 2, we can obtain the probability P_0:

$$P_0 = \frac{1}{\sum_{j=0}^{C-C_h} \frac{\rho^j}{j!} + \sum_{j=C-C_h+1}^{C} \frac{\rho^j a^{j-(C-C_h)}}{j!} + \sum_{j=C+1}^{C+k} \frac{\rho^j a^{j-(C-C_h)}}{C! \prod_{i=1}^{j-C} (C\mu_H + i\mu_Q)}} \tag{11}$$

Now, we define the waiting time of a queued handoff call as the time of an arbitrarily selected handoff call between the moment it is accepted and begin waiting in the queue to the moment it successfully accesses a free channel. Given that the state of the system is when the call arrives and waits in the queue, we denote the waiting time by $W_h(j)$. Clearly, $0 \le q \le k-1$

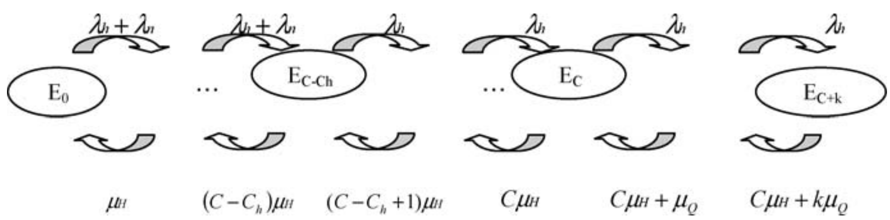

Figure 2. State transition diagram of the queuing traffic model.

and $W_h(j)$ can be obtained by the following formula [5]:

$$W_h(j) = -\frac{1}{\mu_Q} \ln(1 - R_h(j)) \tag{12}$$

where "ln" is the natural logarithmic function and $R_h(j)$ is the dropping probability of an arbitrary selected handoff call, given that the system state is $j = C + q$ just at the instant the call is accepted by the system and waits in the queue. This probability is derived later on in this section. Consequently, the average waiting time of a handoff call, denoted by $\overline{W_h}$, can be obtained by:

$$\overline{W_h} = \frac{\sum_{j=C}^{C+k-1} P_j W_h(j)}{\sum_{j=C}^{C+k-1} P_j} \tag{13}$$

As we can easily conclude, $\overline{W_h}$ is a function of the mean queue service time $\overline{T_Q} = 1/\mu_Q$. Thus, setting an upper bound $(\overline{W_h})_{\text{MAX}}$ for the waiting time in the queue, we can solve for $\overline{T_Q}$ and find the corresponding maximum allowable mean service time at every position. Of course, this solution of $\overline{T_Q}$ should be inside the interval $[0, +\infty)$. From Equation (13), it is obtained that:

$$(\overline{W_h})_{\text{MAX}} = f(\overline{T_Q})_{\text{MAX}} \Rightarrow (\overline{T_Q})_{\text{MAX}} = f^{-1}((\overline{W_h})_{\text{MAX}}) \tag{14}$$

The blocking probability of the new calls is the sum of the probabilities that the state number of the cell is larger than or equal to $C - C_h$. Hence:

$$P_B = \sum_{C-C_h}^{C+k} P_j \tag{15}$$

As we already mentioned, the blocked handover calls join a queue. A handover attempt that enters the queue at the position $q(0 \leq q \leq k - 1)$ will be successful, if it manages to reach the first position of the queue and get a channel before its mean service time becomes greater than the calculated from Equation (14) value. Thus, the handoff blocking probability can be expressed mathematically as:

$$P_{fh} = \left[\sum_{q=0}^{k-1} P_{C+q} \times \text{Pr(attempt\_fails\_given\_it\_enters\_the\_queue\_in\_position\_}(q+1))\right] + P_{C+k}$$

or

$$P_{fh} = \sum_{q=0}^{k-1} P_{C+q} R_h(C + q) + P_{C+k} \tag{16}$$

In order to derive the probability of a handoff failure in the queue $R_h(C+q)$, we assume that:

$$1 - R_h(C+q) = \left[\prod_{i=0}^{q} P(i/i+1)\right] \times \Pr(\text{call\_remains\_in\_queue}) \tag{17}$$

The probability of transition from position $i+1$ to i is denoted by $P(i/i+1)$ in Equation (17) and is contributed by two probabilities [5]:

i. The remaining channel holding time of any of the C calls in progress is smaller than each of the following:
   - The remaining channel holding time of any of the other $(C-1)$ calls in progress.
   - The service time of any of the i waiting handoff calls.
   - The service time of the waiting handoff call of interest.

ii. The remaining service time of any of the i handoff calls waiting in the queue is smaller than each of the following:
   - The channel holding time of any of the C calls in progress.
   - The service time of any of the other $(i-1)$ waiting handoff calls.
   - The service time of the waiting handoff call of interest.

Thus, the transition probability can be obtained by:

$$P(i/i+1) = \frac{C\mu_H + i\mu_Q}{C\mu_H + (i+1)\mu_Q} \tag{18}$$

The second term in Equation (17) is a logical condition that can have only two values. If the mean service time at this position is smaller than or equal to the maximum mean service time threshold (derived by Equation (14)), this term is set to "1". Otherwise, it is set to "0". Thus:

$$\Pr(\text{call\_remains\_in\_queue}) = \begin{cases} 1, & \overline{T_Q} \le (\overline{T_Q})_{\text{MAX}} \\ 0, & \text{otherwise} \end{cases} \tag{19}$$

Finally, by substituting (17), (18), (19) into (16), we have:

$$P_{fh} = \begin{cases} \displaystyle\sum_{q=0}^{k-1} P_{C+q}\left[1 - \prod_{i=0}^{q} \frac{C\mu_H + i\mu_Q}{C\mu_H + (i+1)\mu_Q}\right] + P_{C+k}, & \overline{T_Q} \le (\overline{T_Q})_{\text{MAX}} \\ \displaystyle\sum_{q=0}^{k} P_{C+q}, & \text{otherwise} \end{cases} \tag{20}$$

At this point, it is important to introduce a new probability, which is more important than P_{fh}. When the cell radius is small, the probability that a mobile crosses a cell boundary during call duration is higher. Thus, from the user's point of view, the probability P_F that a call, which is not blocked, is eventually forced into termination is a very significant parameter in mobile systems. This will occur if the call succeeds in each of the first $(k-1)$ handoff attempts that it requires, but fails on the kth attempt. Therefore:

$$P_F = \frac{P_{fh} P_N}{1 - P_H(1 - P_{fh})} \tag{21}$$

Probabilities P_N and P_H in (21) denote the handoff demand of new and handoff calls, respectively and can be obtained by [1]:

$$P_N = \Pr(T_M > T_n) = \int_0^\infty e^{-\mu_M t} f_{Tn}(t)dt \tag{22}$$

$$P_H = \Pr(T_M > T_h) = \int_0^\infty e^{-\mu_M t} f_{Th}(t)dt \tag{23}$$

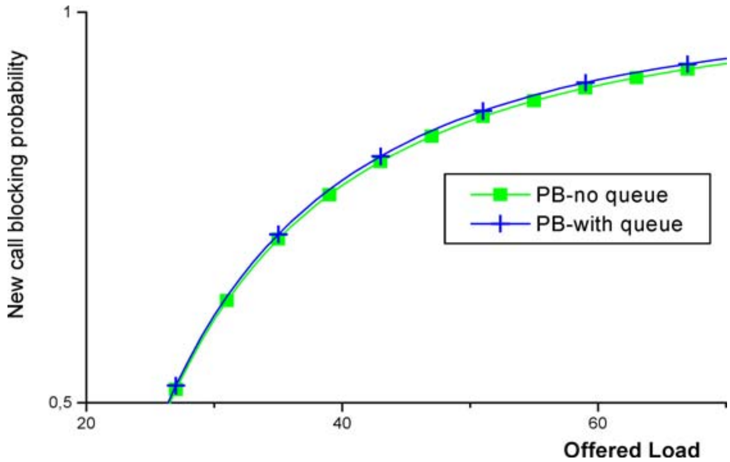

Figure 3. New call blocking probability versus offered load for queue and non-queue strategy.

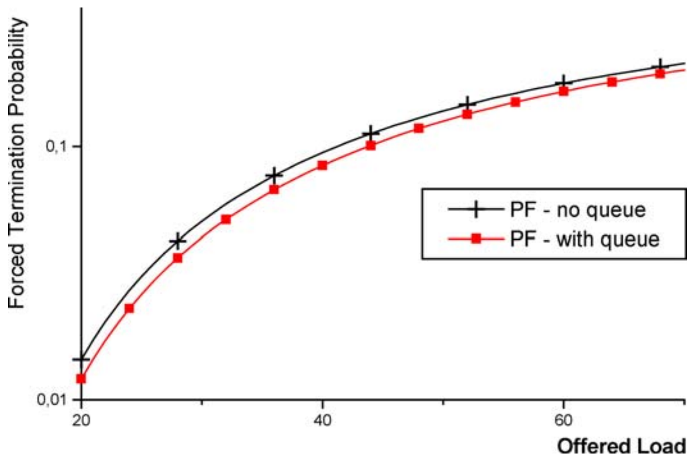

Figure 4. Handover forced termination probability P_F versus offered load for queue and non-queue strategy.

4. Simulation Results and Comparisons

In this section we present the results of our model and some comparisons are made with other known schemes. Generally, our proposed prioritized handover and finite queuing procedure leads to a significant optimization on the handover forced termination probability. The following assumptions have been made during simulation:

- The mean call duration T_M is 120 seconds.
- The maximum speed of a mobile is 60 miles/hour.
- The total number of available channels in the cell is $C = 20$.
- $C_h = 2$ channels are reserved only for handover calls.
- The cell radius is 1 km.
- The handover call to total call is $a \cong \frac{1}{3}$. This value is based on statistical measurements in real cellular systems.
- The queue length is set to $k = 3$.

In order to calculate the other values that are involved in the simulation, we use the appropriate equation presented in this paper. For example, to calculate the mean channel holding time, we substitute the values above in Equations (1)–(3) and find out that $\mu_H \approx \frac{1}{85}$ sec^{-1}.

The probabilities of handoff demand of new and handoff calls in (22) and (23) are found to be $P_N = 0{,}43645$ and $P_H = 0{,}31629$, respectively. Figures 3 and 4 show P_B and P_F, respectively, as a function of the offered load for the prioritized handover scheme and for our proposed handover queuing priority and finite storage scheme. As we notice, our model

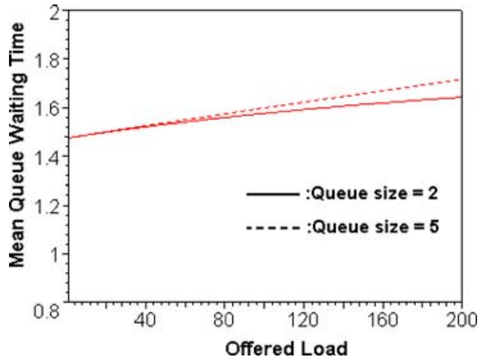

Figure 5. Mean Queue Waiting Time vs. Offered Load for different queue sizes.

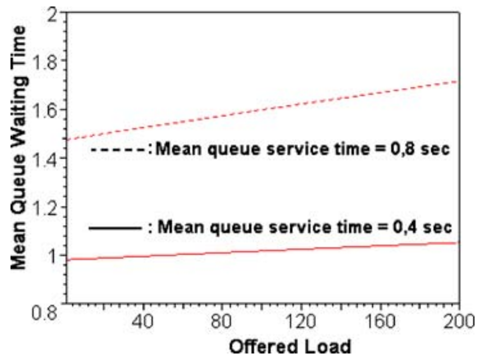

Figure 6. Mean Queue Waiting Time vs. Offered Load for different mean queue service times.

seems to give better results for the forced termination probability, while the new call blocking probability does not increase dramatically.

The relation between service and waiting time is presented in Figures 5 and 6. For various values of the mean service time and for different queue sizes, we notice that, as the offered load increases, the increment in W_h is more significant for a queue size of $k = 2$ than for a size of $k = 5$.

5. Conclusions

This paper deals with a new complex telecommunication traffic model based on prioritized handover and finite storage queuing. The prioritized handover is achieved by reserving a small number of channels only for the handover calls and also, only handover-blocked calls are allowed to enter a finite storage queue. The call arrival processes are assumed to be Poisson and a suitable empirical model obtains the mean channel holding time for both types of calls. For our mathematical analysis, we use a birth-death Markovian process and we derive all the necessary probabilities. The basic idea of our approach is that any blocked handover call should not wait in the queue for a very long time, either if this call is still in the handover area. Finding the suitable function for the mean waiting time in the queue, we calculate an upper bound for the mean service time at each queue position. As it is noticed from the figures, our model gives satisfactory results for the derived handover forced termination probability.

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