Analytic Modeling of Handoffs in Wireless Cellular Networks*

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Abstract

In this paper, we report our recent work on closed form solutions to the blocking and dropping probability in wireless cellular networks with handoff. First, we develop a performance model of a cell in a wireless network where the effect of handoff arrival and the use of guard channels are included. Fast recursive formulas for the loss probabilities of new calls and handoff calls are given. Algorithms to determine the optimal number of guard channels and the optimal number of channels are developed. To determine the handoff arrival rate into a cell, a fixed-point iteration scheme is proposed, and the uniqueness of the fixed-point is shown. Then, we allow for failure and repair of channels and hence provide a performability analysis for cellular systems. We present a hierarchical model combining both perofrmance and availability and its closed form solution. Performability measures of interest are explicitly given.

Key words: Channel allocation, Markov models, Optimization, Performance, Hard handoff.

1 Introduction

The rapid growth in the demand for mobile communications has led to an intense research effort to achieve an efficient use of the scarce spectrum allocated for cellular communications. In a cellular system, mobile subscribers (MSs) are provided with telephone service within a geographical area. The service area is divided into multiple adjacent cells. MSs communicate via radio links to base stations (BSs), one for each cell. When an MS moves across a cell boundary, the channel in the old BS is released and an idle channel is required in the new BS. This phenomenon is called *handoff*. Handoff is an important function of mobility management. In mobile systems such as AMPS [1], global system for mobile communication (GSM)[2], DECT [3], D-AMPS [4], and PHS [5], *hard handoff* is employed [6,7]. In hard handoff, the old radio link is broken before the new radio link is estabished, and an MS always communicates with one BS at any given time. In the handoff procedure, the network needs to set up the new voice path for the handoff call. Some CDMA systems [8] and GSM with macrodiversity [2] utilize *soft handoff* where an MS may communicate with the outside world using multiple radio links through different BSs at the same time. During handoff, the signaling and voice information from multiple BSs are typically combined (or bridged) at the mobile switching center (MSC). In some soft handoff systems, an MS may connect up to three or four radio links at the same time. Thus, within the overlay area of cells, an MS can connect to multiple BSs.

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Loss probabilities or formulas for new call blocking and handoff call dropping, have been widely employed to evaluate call admission control (CAC) strategies for wireless cellular networks. When a new call (NC) is attempted in an cell covered by a BS, the NC is connected if an idle channel is available in the cell. Otherwise, the new call is *blocked.* Similarly, if an idle channel exists in the target cell, the handoff call (HC) continues nearly transparently to the MS. Otherwise, the HC is *dropped.*

The Erlang-B formula has been normally used to compute the loss probability in wireline networks. But, this formula cannot be used in cellular wireless networks due to the phenomenon of handoff. The current researches on handoff mainly involve following two issues: (1) How does the handoff process affect performance of wireless cellular system; (2) How do we design handoff scheme so that channel resources are used efficiently and quality of service (QoS) is still guaranteed. Recently, many analytical and simulation models that characterize the handoff problems have been presented [9-13]. Also, many handoff schemes have been developed to reduce or optimize the loss probabilities [9-20]. However, closed form solutions to the loss formulas have not been reported by others. This paper reviews our recent work reported in papers [13-15].

In Section 2, We present analytic modeling for cellular systems with hard handoff. The closed form loss formulas, fixed-point strategy, and optimization problems are demonstrated. In Section 3, considering possibility of failures in the system, we extend the previous work to build an analytic model for the cellular system with failures, obtaining the corresponding loss formulas. Finally, conclusions are made in Section 4.

2 Loss formulas and optimization for cellular systems with hard handoff [13]

2.1 Model Description

Consider the performance model of a single cell in a cellular wireless communication network. Let λ_n be the rate of Poisson arrival stream of new calls and λ_h be the rate of Poisson stream of handoff arrivals. Let μ_c be the rate at which an ongoing call (new or handoff) completes service and let μ_h be the rate at which the mobile engaged in the call departs the cell. Also assume that a limited number of channels, N, in the channel pool. When an idle channel is available in the channel pool and a handoff call arrives, the call is accepted and a channel is assigned to it. Otherwise, the handoff call is dropped. When a new call arrives, it is accepted provided that at least $g+1$ idle channels are available in the channel pool; otherwise, the new call is blocked. Here g is the number of guard channels [18]. Assume that $g < N$ in order not to exclude new calls altogether.

2.2 Loss Probabilities

Let $C(t)$ denote the number of busy channels at time t, then $\{C(t), t \geq 0\}$ is a continuous time markov chain and in particular it is a birth-death process as shown in Figure 1.

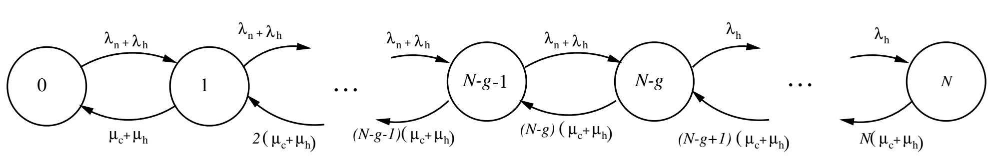

Figure 1: Markov Chain Model of Wireless Handoff

Define the steady-state probability:

$$p_n = \lim_{t\to\infty} Prob(C(t) = n), \qquad n \in \Omega = \{0, 1, 2, \ldots, N\}.$$

Let $\lambda = \lambda_n + \lambda_h$, $\mu = \mu_c + \mu_h$. $A = \dfrac{\lambda}{\mu}$, $A_1 = \dfrac{\lambda_h}{\mu_c + \mu_h}$. Then we have an expression for p_n after solving the Kolmogorov equations:

$$p_n = p_0 \begin{cases} \dfrac{A^n}{n\,!} & n \le N-g \\[2ex] \dfrac{A^{N-g}}{n\,!} A_1^{n-(N-g)} & n \ge N-g \end{cases}$$

where

$$p_0 = \frac{1}{\displaystyle\sum_{n=0}^{N-g-1} \frac{A^n}{n\,!} + \sum_{n=N-g}^{N} \frac{A^{N-g}}{n\,!} A_1^{n-(N-g)}}.$$

Now we can write expression for the dropping probability for handoff calls:

$$P_d(N,g) = p_N = \frac{\dfrac{A^{N-g}}{N\,!} A_1^{g}}{\displaystyle\sum_{n=0}^{N-g-1} \frac{A^n}{n\,!} + \sum_{n=N-g}^{N} \frac{A^{N-g}}{n\,!} A_1^{n-(N-g)}}. \tag{1}$$

Similarly, the expression for the blocking probability of new calls:

$$\begin{aligned} P_b(N,g) = \sum_{n=N-g}^{N} p_n &= \frac{\displaystyle\sum_{n=N-g}^{N} \frac{A^{N-g}}{n\,!} A_1^{n-(N-g)}}{\displaystyle\sum_{n=0}^{N-g-1} \frac{A^n}{n\,!} + \sum_{n=N-g}^{N} \frac{A^{N-g}}{n\,!} A_1^{n-(N-g)}} \\ &= A^{N-g} \frac{\displaystyle\sum_{k=0}^{g} \frac{A_1^k}{(k+N-g)\,!}}{\displaystyle\sum_{n=0}^{N-g-1} \frac{A^n}{n\,!} + \sum_{n=N-g}^{N} \frac{A^{N-g}}{n\,!} A_1^{n-(N-g)}}. \end{aligned} \tag{2}$$

Observe that if we set $g = 0$ then equation (2) reduces to the classical Erlang-B loss formula. In fact, setting $g = 0$ in equation (1) also provides the Erlang-B loss formula. In the above formulas A is the total traffic in *Erlangs* as seen by a cell, while A_1 is the handoff traffic in *Erlangs*.

When the number of channels, N, is large, the above two loss formulae are not convenient to use as overflow and underflow might occur due to factorials and large powers of A and A_1. In most wireless systems, N is large leading to numerical difficulties in the direct use of the loss formulae (1) and (2).

In the next subsection we show numerically stable computation for the loss probabilities that avoids the computation of factorials and large powers of loads in *Erlangs*.

2.3 Recursive Computation and Fixed Point Iteration

Let

$$E_B(A,N) = \frac{\frac{A^N}{N\,!}}{1 + A + \frac{A^2}{2\,!} + \ldots + \frac{A^N}{N\,!}} \tag{3}$$

be the Erlang-B loss formula.

Then we can show the following:

$$P_d(N,0) = P_b(N,0) = E_B(A,N)$$

Thus to compute the loss probability in case there are no guard channels ($g = 0$), we simply use the standard loss formula with total traffic A in *Erlangs*. Observe that the traffic includes both new calls and handoff calls. The service rate includes both call completion and handoff out into adjacent cells.

In the case the number of guard channels $g > 0$, let $N_1 = N - g$ be the number of shared channels. Now we can use the following recursive formula (for a proof, see [13]):

Let $P_d(N_1, 0) = E_B(A, N_1)$ and compute

$$P_d(N_1 + k, k) = \frac{P_d(N_1 + (k-1), k-1)}{\frac{N}{\alpha A} + P_d(N_1 + (k-1), k-1)}, \qquad k = 1, 2, \ldots, g. \tag{5}$$

Similarly for the new call blocking probability, let $P_b(N_1, 0) = E_B(A, N_1)$ and compute

$$P_b(N_1 + k, k) = \frac{\frac{N}{\alpha A} P_b(N_1 + (k-1), k-1) + P_d(N_1 + (k-1), k-1)}{\frac{N}{\alpha A} + P_d(N_1 + (k-1), k-1)}, \quad k = 1, 2, \ldots, g \tag{6}$$

where $\alpha A = A_1$ is the traffic in *Erlangs* due to handoff arrivals.

In the above derivation of loss formulae, we assumed that handoff call arrival rate, λ_h is given. In practice, the value of λ_h needs to be determined as a function of λ_n, μ_c, μ_h, N and g. We assume that all cells are statistically identical. Thus the rate of handoff out from a cell equals the rate at which handoff calls arrive into a cell. In other words, the steady-state *handoff-out* throughput should equal the arrival rate (λ_h) of the *handoff-in* traffic.

Let $T(x)$ denote the throughput of *handoff-out* for $\lambda_h = x$ when the other parameters λ_n, μ_c, μ_h, N and g are fixed. By definition:

$$T(x) = \mu_h \sum_{n=1}^{N} n p_n$$

After substituting for p_n, the above equation becomes,

$$T(x) = \frac{\mu_h}{\mu} \lambda_n (1 - P_b(x)) + x \frac{\mu_h}{\mu} (1 - P_d(x)).$$

If we consider $x = T(x)$, we get

$$x = \frac{\mu_h \lambda_1 (1 - P_b(x))}{\mu - \mu_h (1 - P_d(x))}.$$

Let the function $f(x)$ be, the right-hand-side of the above equation,

$$f(x) = \frac{\mu_h \lambda_1 (1 - P_b(x))}{\mu - \mu_h (1 - P_d(x))}. \tag{10}$$

It is easy to note that $f(x)$ is a decreasing function of x on $[0, +\infty]$. Moreover:

$$f(0) = \frac{\mu_h \lambda_n}{\mu_1}(1 - E_B(A_0, N - g)) \quad \text{with } A_0 = \frac{\lambda_n}{\mu}, \qquad \text{and} \lim_{x \to +\infty} f(x) = 0. \tag{11}$$

So the solution of $x = f(x)$ on $[0, +\infty]$ is unique. Denote this unique solution by $\tilde{x}$. This value can be obtained using the iterative procedure

$$x^k = f(x^{k-1}) \qquad k = 1, 2, ... \tag{12}$$

with for example $x^0 = \frac{\mu_h \lambda_n}{\mu_c}$. Because of the monotonicity of $f(x)$, $P_b(x)$ and $P_d(x)$, it is also easy to observe that $P_b(\tilde{x}) \leq P_b(x^0)$ and $P_d(\tilde{x}) \leq P_d(x^0)$. So x^0 can be used as an approximation to $\tilde{x}$. In fact since $P_b(x)$ and $P_d(x)$ are expected to be small values, the approximation x^0 should be very good in most situations. Our experiments show that the iteration above converges very fast (within a few iterations) in practice.

2.4 Optimal Values of g and N

We consider the problem of minimizing both the new call blocking probability as well as the handoff dropping probability. Hence we have a multiobjective optimization problem and the decision variables are the number of guard channels, g, and the number of channels, N. In a easy case of the problem, we fix N and consider only g as the decision variable. Given the two objectives, there are several different ways we can set up the optimization problem on hand. We can pick either P_b or P_d as the objective function to be minimized and we impose a constraint on the other one. Thus we consider two representative optimization problems $\mathbf{O_1}$: and $\mathbf{O_2}$:.

$\mathbf{O_1}$: Given A, N and α, determine the optimal integer value of g so as to

$$\begin{aligned} &\text{minimize} \quad P_b(g) \\ &\text{such that} \quad P_d(g) \leq P_{d\mathbf{0}} \end{aligned}$$

Based on property $P_d(N, g) < P_d(N, g-1)$, we first obtain the smallest value of g such that $P_d(g) \leq P_{d\mathbf{0}}$. Then using the property $P_b(N, g) > P_b(N, g-1)$ we see that such a value of g will minimize $P_b(g)$. Thus the optimal value of g is obtained using a simple one dimensional search over the range $\{0, 1, 2, ..., N-1\}$ for g such that

$$g^* = \min \{g \mid P_d(g) \leq P_{d\mathbf{0}}\}.$$

$\mathbf{O_2}$: Given A and α, determine the optimal integer values of N and g so as to

$$\begin{aligned} &\text{minimize } N \\ &\text{such that} \begin{cases} P_b(N, g) \leq P_{b\mathbf{0}} \\ P_d(N, g) \leq P_{d\mathbf{0}} \end{cases} \end{aligned}$$

In order to solve the optimization problem $\mathbf{O_2}$ above, we consider the distinguish three cases depending upon the values of $P_{d\mathbf{0}}$ and $P_{b\mathbf{0}}$. For further details, see [13] .

3 Loss formulas for hard handoff systems with failures [14]

The last section provided pure performance analysis-based formulas for cellular networks. In this section we allow for failure and repair of channels and hence provide a performability analysis for cellular systems.

3.1 Wireless cellular systems with failures

A TDMA system with hard handoff in which a cell has multiple base repeaters, say N_b, is considered in this model. Each base repeater provides a number of channels, say M, for mobile terminals to communicate with the system. Therefore a total of N_bM channels are available when the whole system is working properly. Normally, one of the channels is dedicated to transmitting control messages. Such a channel is called control channel. The total number of available talking or voice channels is $N_bM - 1$. We also assume that the control channel is selected randomly out of N_bM channels. Failure of the control channel will cause the whole system to fail. To avoid this undesirable situation, an automatic protection switching (APS) scheme is suggested in [25] so that the system automatically selects a channel from the rest of the available channels to substitute the failed control channel. If all channels are in use (talking), then one of them is forcefully terminated and is used as the control channel.

A cell as a whole is subject to failures which make all channels in accessible, causing a full outage. In practice, this type of failures may occur when the communication links between base station controller and base repeaters do not function properly, or critical function units (such as base station controller) fail. In this model, we will refer to this type of failure as the platform failure. Each base repeater is also subject to failure which disables the channels that it provides. In a system without APS, if a failed base repeater happens to be the one hosting the control channel, it results in a full outage, same as the situation caused by a platform failure.

We use the traditional two-level performability model: we first present an availability model which accounts for the failure and repair of base repeaters; second, we use a performance model to compute performance indices given the number of non-failed base repeaters; finally, we combine them together and give corresponding loss formulas.

3.2 The availability model

All failure events are assumed to be mutually independent. Times to platform failures and repair are assumed to be exponentially distributed with mean $1/\lambda_s$ and $1/\mu_s$, respectively. Also assumed is that times to base repeater failures and repair are exponentially distributed with mean $1/\lambda_b$ and $1/\mu_b$ respectively, and that a single repair facility is shared by all the base repeaters.

Let $s \in S = \{0, 1\}$ denote a binary value indicating whether or not the system is down due to a platform failure (0: system down due to a platform failure; 1: no platform failure has occurred). Also let $k \in B = \{0, 1, \cdots, N_b\}$ denote the number of non-failed base repeaters. The 2-tuple $(s, k), s \in S, k \in B$ defines a state in which the system is undergoing a (no) platform failure if $s = 0$ (if $s = 1$) and k base repeaters are up. The underlying stochastic process is a homogeneous continuous time Markov chain with state space $S \times B$. Let $P(s, k; N_b)$ be the corresponding steady state probability. The state diagram of this irreducible CTMC is depicted in Figure 2.

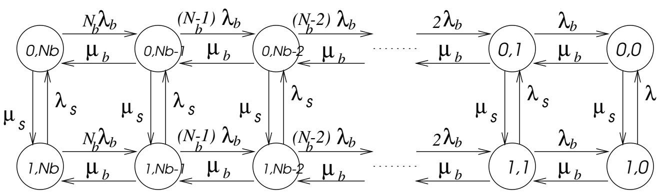

Figure 2: Markov chain of Availability Model

Solving the Markov chain, we have

$$P(s,k;N_b) = \begin{cases} \dfrac{\lambda_s}{\lambda_s+\mu_s}\dfrac{1}{k!}\left(\dfrac{\mu_b}{\lambda_b}\right)^k\left[1+\displaystyle\sum_{j=1}^{N_b}\dfrac{1}{j!}\left(\dfrac{\mu_b}{\lambda_b}\right)^j\right]^{-1}, & \text{if } s=0, \\ \dfrac{\mu_s}{\lambda_s+\mu_s}\dfrac{1}{k!}\left(\dfrac{\mu_b}{\lambda_b}\right)^k\left[1+\displaystyle\sum_{j=1}^{N_b}\dfrac{1}{j!}\left(\dfrac{\mu_b}{\lambda_b}\right)^j\right]^{-1}, & \text{if } s=1. \end{cases} \quad (14)$$

The system is down in all the states in which either the system has a platform failure that brings the whole system down, or in a system without APS, a base repeater hosting the control channel fails, or the system even without platform failure has no working base repeater left. For a system without APS, the probability that one of the $(N_b - k)$ failed base repeaters happens to host the control channel is $(N_b - k)/N_b$. Let $\overline{A}(N_b)$ denote the steady state system unavailability:

$$\overline{A}(N_b) = \begin{cases} \displaystyle\sum_{k=0}^{N_b} P(0,k;N_b) + \sum_{k=0}^{N_b} P(1,k;N_b)\frac{N_b-k}{N_b}, & \text{w/o APS} \\ \displaystyle\sum_{k=0}^{N_b} P(0,k;N_b) + P(1,0;N_b), & \text{w/ APS.} \end{cases} \quad (15)$$

3.3 Performability

For each of the states of the availability model of Figure 2, Equation(2) and (3) in Section 2 provide performance indices given the number of non-failed repeaters or channels.

We notice that calls can be blocked (or dropped) due to system *being down* or system *being full*. The former type of loss is captured by the pure availability model while the latter type of loss is captured by the pure performance model. We now wish to combine the two types of losses. The primary vehicle for doing this is to determine pure performance losses for each of the availability model states and attach these loss probabilities as reward rates (or weights) to these states. Such a Markov reward model has been called a performability model [16, 17, 19]. We list reward rates for the states of the availability model in Table 1 for systems without APS and Table 2 for system with APS. Let us first consider states of system being down.

Clearly, for both systems without and with APS, a cell is not able to accept any new calls or handoff calls if it has platform failure which corresponds to the states $(0, k)$ for $k = 0, \cdots, N_b$, or all base repeaters are down which corresponds to the state $(1, 0)$. Therefore, reward rates of both overall new call blocking and handoff call dropping are 1's.

In addition, for a system without APS, control channel down may occur in states $(1, k)$ for $k = 1, \cdots, N_b$ with probability $(N_b - k)/N_b$ and cause new call blocking and handoff

<table>
<tr><th rowspan="2">State (s, k)</th><th colspan="2">Reward rate</th></tr>
<tr><th>New call blocking</th><th>Handoff call dropping</th></tr>
<tr><td>$(0, k)$, for $k = 0, \cdots, N_b$</td><td>1</td><td>1</td></tr>
<tr><td>$(1, 0)$</td><td>1</td><td>1</td></tr>
<tr><td>$(1, k)$, for $k = 1, \cdots, N_b$</td><td>1, if $kM - 1 \le g$
$\frac{N_b - k}{N_b} +$
$P_b(kM - 1, g)\frac{k}{N_b}$, o.w.</td><td>$\frac{N_b - k}{N_b} +$
$P_d(kM-1, g)\frac{k}{N_b}$</td></tr>
</table>

Table 1: Reward rates for systems without APS

call dropping. This corresponds to the rates with $(N_b - k)/N_b$ in the last row of Table 1. All cases mentioned above contribute to system unavailability, $\overline{A}(N_b)$. Hence, system

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$P_b(kM - 1, g)$, o.w.</td><td>$P_d(kM - 1, g)$</td></tr>
</table>

Table 2: Reward rates for systems with APS

unavailability, $\overline{A}(N_b)$, also consists of one of the parts of the overall new call blocking probability and handoff call dropping probability.

We now consider states in which the system is not undergoing a full outage caused by failures of platform, control channel (if system w/o APS) or all base repeaters being down.

The corresponding states are $(1, k)$ for $k = 1, \cdots, N_b$. The total number of available channels for state $(1, k)$ is $kM - 1$. Thus, new call blocking probability and handoff call dropping probability in these states are $P_b(kM - 1, g)$ and $P_d(kM - 1, g)$, respectively. Thus, these probabilities are used as reward rates to these states for overall new call blocking and handoff call dropping.

For a system without APS, we note that the probability of not having the control channel down in state $(1, k)$ for $k > 0$ is k/N_b. Therefore, the reward rates, $P_b(kM - 1, g)$ and $P_d(kM - 1, g)$, are also weighted by k/N_b (shown in the last row of Table 1).

Also, in case that the number of idle channels is less than the number of guard channels, *i.e.*, $kM - 1 < g$ for states $(1, k)$, $k = 1, \cdots, N_b$, a cell is not able set up any new calls because all available channels are reserved for handoff calls. Hence, the reward rates for new call blocking assigned to the corresponding states are 1's.

Now let $G = \lfloor (g + 1)/M \rfloor$. Summarizing Table 1 and Table 2, the overall call blocking probability can be written as the expected steady state reward rate,

$$P_b^o(N_b, M, g) = \overline{A}(N_b) + \begin{cases} \mathbf{1}(G > 0) \sum_{k=1}^{G} P(1, k; N_b) \left(\frac{k}{N_b}\right) \\ \quad + \sum_{k=G+1}^{N_b} P(1, k; N_b) P_b(kM-1,\ g) \left(\frac{k}{N_b}\right), & \text{w/o APS} \\ \mathbf{1}(G > 0) \sum_{k=1}^{G} P(1, k; N_b) \\ \quad + \sum_{k=G+1}^{N_b} P(1, k; N_b) P_b(kM-1,\ g), & \text{w/ APS} \end{cases} \tag{16}$$

where $\mathbf{1}(e)$ is the indicator function: $\mathbf{1}(e) = 1$ if expression e is true; $\mathbf{1}(e) = 0$, otherwise. Similarly the overall handoff call dropping probability can be given as

$$P_d^o(N_b, M, g) = \overline{A}(N_b) + \begin{cases} \sum_{k=1}^{N_b} P(1, k; N_b) P_d(kM-1,\ g) \frac{k}{N_b}, & \text{w/o APS} \\ \sum_{k=1}^{N_b} P(1, k; N_b) P_d(kM-1,\ g), & \text{w/ APS.} \end{cases} \tag{17}$$

4 Conclusions

We have presented our research achievements on handoff performance in wireless cellular networks. We developed tractable analytic models for the wireless system with hard handoff, and hard handoff including channel failures. We obtained closed form solutions to new call blocking probabilities and handoff call dropping probabilities. To avoid possible overflow and underflow during computations of the loss formulas, we derived fast recursive expressions for some loss formulas. In addition, We developed and solved some optimization problems for the loss formulas. Finally, we proposed fixed-point iteration scheme to determine handoff arrival rate into a cell.

Future research will consider the modeling and analysis of performability in TDMA system with general handoff arrivals, performability in CDMA system, and multiple level QoS in wireless internet system.

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