A Single-Threshold Model for Handoff Traffic Analysis in Cellular CDMA Networks

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***Abstract*—Small cells are expected to play an important role in future mobile networks. In such environments, proper handling of handoff traffic is of major importance. In this paper, we propose the single-threshold model for the analysis of handoff traffic in cellular CDMA networks. Based on this model, we are able to determine analytically the uplink blocking probabilities of handoff and new calls. This is done by describing the CDMA system as a Discrete-Time Markov Chain and by deriving an efficient recursive formula for the calculation of system state probabilities. The proposed analytical model is verified via simulation studies.**

Keywords—handoff; cdma; call blocking probability; recursive formula.

I. INTRODUCTION

The Code Division Multiple Access (CDMA) techniques have been used in the current generation mobile networks and are expected to play an important role in future 5G networks. Some of the advantages of CDMA-based techniques over other competing technologies include enhanced security, efficient frequency spectrum utilization, and improved signal quality.

According to the traditional cellular model, the geographical area is divided into cells, and each of them is controlled by a Base Station (BS). Different BSs communicate with each other through the core network (usually fixed and wired). Although, in future mobile networks it is envisioned the introduction of intelligent BSs that will be able to communicate directly with each other for both signalling and data traffic [1]. Mobile Users (MUs), located in the same or different cells, communicate with each other through the corresponding BSs. The communication link from MUs to BS is referred to as uplink, whereas the communication link from BS to MUs is referred to as downlink. Due to non-orthogonality of the CDMA codes, a new MU arriving to a cell will cause interference to other MUs in the same and neighbouring cells. Therefore, Call Admission Control (CAC) is performed upon a call arrival, in order to protect the Quality-of-Service (QoS) of existing MUs. This may result in the blocking of the newly arriving call.

In this work, we consider two types of call blocking: new-call blocking and handoff-call blocking. The first type refers to the call blocking upon the initial connection establishment, whereas the second type refers to the blocking of already accepted in-service calls when they move from one cell to another. The procedure of moving between neighbouring cells, while a call is in progress, is called handoff. The CAC policy is expected to guarantee that the handoff-call blocking probability will be significantly lower than that of the new-call blocking.

In this paper, we model a cellular CDMA system as a Discrete-Time Markov Chain (DTMC). Our analysis is based on the classical Erlang Multirate Loss Model (EMLM) [2], [3] and its extension for single-threshold model [4], [5], which has been proposed for wired connection-oriented networks. We extend [2]-[5] by considering the handoff traffic and soft network capacity of CDMA systems.

This paper is organized as follows. In Section II, we present the literature review. In Section III, we describe our proposed model for cellular CDMA systems. In Section IV, we present a detailed calculation of local blocking probabilities. In Section V, we derive equations for an efficient calculation of call blocking probabilities. In Section VI, we study the performance of the proposed approach by means of computer simulations. We conclude and discuss our future work in Section VII.

II. LITERATURE REVIEW

Many important teletraffic models have been proposed for the determination of *new-call* blocking probabilities in cellular CDMA networks [6]-[18]. In [6], the call blocking calculation in the uplink of a W-CDMA cell is based on an extension of the EMLM. The authors assume that calls arrive in the system according to a Poisson process. This work was extended in [7], by incorporating elastic and adaptive traffic, and in [8], [9] by considering a quasi-random call arrival process. In [10], an efficient CAC scheme for CDMA systems has been proposed and evaluated. In [11], the authors propose an analytical model

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for multi-service cellular networks servicing multicast connections. An extension of [8] has been proposed in [12] to model elastic and adaptive traffic. A different approach that includes interference cancellation has been proposed in [13]-[15]. In [16], the authors evaluate the performance of W-CDMA systems with different QoS requirements. In [17], a teletraffic model for a W-CDMA cell with finite number of channels and finite number of traffic sources is presented. This model has been extended in [18] to provide equalization of call congestion probabilities among different service-classes.

Some of the aforementioned models have been extended for the analysis of *handoff-call* blocking probabilities [19]-[22]. In [19], a model for W-CDMA systems with a soft handoff mechanism has been proposed. In [20], the model of [8] has been extended for the calculation of handoff-call blocking probabilities. In [21] and [22], the model of [6] has been enhanced with a CAC for handoff traffic. While most of the works concentrate on the uplink, a few papers study the downlink of CDMA systems as well [23], [24].

In this paper, we concentrate on the uplink of cellular CDMA systems and handoff traffic. In particular, we extend [21] by enabling two contingency bandwidth requirements of the arriving calls. If the system is heavily loaded (above a predefined threshold), then the call will request less bandwidth compared with the case of lightly loaded systems.

III. Model Description

Consider a CDMA system that supports K independent service-classes. We examine a reference cell surrounded by neighbouring cells in the uplink direction (calls from MUs to BS).

The following QoS parameters characterize a service-class k (k=1,…, K) new call:

- $R_{k,N}$: Transmission bit rate.
- $(E_b / N_0)_{k,N}$: Bit error rate (BER) parameter.

The offered traffic-load (in erl) of service-class k new calls is Poisson and denoted as $a_{k,N}$. For our analysis, we express later in the paper the different service's QoS requirements as different resource/bandwidth requirements.

In a similar way, the QoS parameters of a service-class k handoff call are defined as:

- $R_{k,H}$: Transmission bit rate.
- $(E_b / N_0)_{k,H}$: BER parameter.

The offered traffic-load (in erl) of service-class k handoff calls is denoted as $a_{k,H}$. We assume perfect power control. That is, at the BS, the received power from each service-class k call is the same and equal to P_k. Recall that in CDMA systems all MUs transmit within the same frequency band. Therefore, signals generated by MUs cause interference to each other. We distinguish the *intra-cell interference*, I_{intra}, caused by users of the reference cell and the *inter-cell interference*, I_{inter}, caused by users of the neighbouring cells. We also consider the existence of the thermal noise, P_N, which corresponds to the interference of an empty system.

The CAC in CDMA systems is performed by measuring the *noise rise*, *NR*, defined as the ratio of the total received power at the BS, I_{total}, to the thermal noise power, P_N [6]:

$$NR = \frac{I_{total}}{P_N} = \frac{I_{intra} + I_{inter} + P_N}{P_N} \tag{1}$$

When a new call arrives, the CAC estimates the noise rise and if it exceeds a maximum value, $NR_{\max}$, the new call is blocked and lost.

A service-class k call alternates between *active* (transmitting) and *passive* (silent) periods. This behavior is described by the *activity factor*, v_k, which represents the fraction of the call's *active* period over the entire service time ($0 < v_k \le 1$). Users that at a time instant occupy system resources are referred to as *active users*.

The *cell load, n*, is defined as the ratio of the received power from all *active* users (at the reference or neighbouring cells) to the total received power:

$$n = \frac{I_{intra} + I_{inter}}{I_{intra} + I_{inter} + P_N} \tag{2}$$

Hence from (1) and (2) we can derive the relation between the *noise rise* and the *cell load*:

$$NR = \frac{1}{1-n} \quad \text{and} \quad n = \frac{NR-1}{NR} \tag{3}$$

We define the maximum value of the *cell load*, $n_{\max}$, as the *cell load* that corresponds to the maximum *noise rise*, $NR_{\max}$. A typical value in W-CDMA systems is $n_{\max} = 0.8$ and it can be considered as the shared system resource [6].

The *load factor*, $L_{k,N}$, given in (4) can be considered as the resource/bandwidth requirement of a service-class k new call:

$$L_{k,N} = \frac{(E_b / N_0)_{k,N} * R_{k,N}}{W + (E_b / N_0)_{k,N} * R_{k,N}} \tag{4}$$

By W we denote the chip rate of the W-CDMA carrier which is 3.84 Mcps.

The *cell load*, *n*, can be written (see (7) below) as the sum of the *intra-cell load*, n_{intra} (*cell load* that derives from the *active* users of the reference cell), and the *inter-cell load,* n_{inter} (*cell load* that derives from the *active* users of the neighbouring cells). They are defined in (5) and (6), respectively:

$$n_{intra} = \sum_{k=1}^{K} m_{k,N} L_{k,N} \tag{5}$$

where m_k is the number of *active calls* among service-class k new calls.

$$n_{inter} = (1 - n_{max}) \frac{I_{inter}}{P_N} \quad (6)$$

$$n = n_{intra} + n_{inter} \quad (7)$$

In this work, we adopt the following CAC condition at the BS in order to decide whether to accept a new service-class k call or not:

$$n + L_{k,N} \le n_{\max,N} \quad (8)$$

Similarly, the condition for the acceptance of a handoff service-class k call is:

$$n + L_{k,H} \le n_{\max,H} \quad (9)$$

where the derivation of $L_{k,H}$ is calculated similarly to (4).

IV. LOCAL BLOCKING PROBABILITIES

Due to the condition of (8), the probability that a new service-class k call is blocked when arriving at an instant with *intra-cell load*, n_{intra}, is called Local Blocking Probability (LBP) and can be calculated by [21]:

$$\beta_{k,N}(n_{intra}) = P(n_{intra} + n_{inter} + L_k > n_{max,N}) \quad (10)$$

In a similar way, we define the LBP for a handoff service-class k call:

$$\beta_{k,H}(n_{intra}) = P(n_{intra} + n_{inter} + L_k > n_{max,H}) \quad (11)$$

In order to calculate the LBP of (10) we can use (4)-(7). We notice that the only unknown parameter is the *inter-cell interference*, I_{inter}. Similarly to [21], we model I_{inter} as a lognormal random variable (with parameters μ_I and σ_I), that is independent of the *intra-cell interference*. Hence, the mean, $E[I_{inter}]$, and the variance, $Var[I_{inter}]$, of I_{inter} are calculated by (12) and (13):

$$E[I_{inter}] = e^{\mu_I + \frac{\sigma_I^2}{2}} \quad (12)$$

$$Var[I_{inter}] = (e^{\sigma_I^2} - 1) e^{2\mu_I + \sigma_I^2} \quad (13)$$

Consequently, because of (6), the *inter-cell load*, n_{inter}, will also be a lognormal random variable. Its mean, $E[n_{inter}]$, and variance, $Var[n_{inter}]$, are given by (14) and (15), respectively:

$$E[n_{inter}] = e^{\mu_n + \frac{\sigma_n^2}{2}} = \frac{1 - n_{max}}{P_N} E[I_{inter}] \quad (14)$$

$$Var[n_{inter}] = (e^{\sigma_n^2} - 1) e^{2\mu_n + \sigma_n^2} = (\frac{1 - n_{max}}{P_N})^2 Var[I_{inter}] \quad (15)$$

where μ_n and σ_n are the parameters of n_{inter}, which can be found by solving (16) and (17):

$$\mu_n = \ln(E[I_{inter}]) - \frac{\ln(1 + CV[I_{inter}]^2)}{2} + \ln(1 - n_{max}) - \ln(P_N) \quad (16)$$

$$\sigma_n = \sqrt{\ln(1 + CV[I_{inter}]^2)} \quad (17)$$

The coefficient of variation $CV[I_{inter}]$ is defined as:

$$CV[I_{inter}] = \frac{\sqrt{Var[I_{inter}]}}{E[I_{inter}]} \quad (18)$$

Note that (10) can be rewritten as:

$$1 - \beta_{k,N}(n_{intra}) = P(n_{inter} \le n_{max,N} - n_{intra} - L_{k,N}) \quad (19)$$

The Right Hand Side of (19), is the cumulative distribution function of n_{inter}. It is denoted by $P(n_{inter} \le n) = F_n(x)$ and can be calculated from:

$$F_n(x) = \frac{1}{2}[1 + erf(\frac{\ln x - \mu_n}{\sigma_n \sqrt{2}})] \quad (20)$$

where $erf(\bullet)$ is the well-known *error function*.

Hence, if we substitute $x = n_{\max,N} - n_{intra} - L_{k,N}$ into (20), from (19) we can calculate the LBP of new service-class k calls as follows:

$$\beta_{k,N}(n_{intra}) = \begin{cases} 1 - F_n(x), & x \ge 0 \\ 1, & x < 0 \end{cases} \quad (21)$$

Following a similar analysis, we can derive the LBP of handoff service-class k calls as follows:

$$\beta_{k,H}(n_{intra}) = \begin{cases} 1 - F_n(x), & x \ge 0 \\ 1, & x < 0 \end{cases} \quad (22)$$

V. STATE AND CALL BLOCKING PROBABILITIES

A. State Probabilities

As stated before, in CDMA networks the *cell load* can be considered as a shared system resource and the *load factor* as the resource requirement of a call. Thus, we can use a modification of the Kaufman-Roberts recursion (K-R recursion) used for the determination of the link occupancy distribution in the EMLM [3], [4], for the calculation of *state probabilities* in CDTM systems. Below we present five steps needed for the modification.

The discretization of the *cell load*, n, and the *load factor*, $L_{k,N}$, is performed with the use of the *basic cell load unit*, g:

$$C = \frac{n_{max}}{g} \tag{23}$$

$$b_{k,N} = \text{round}\left(\frac{L_{k,N}}{g}\right) \tag{24}$$

where C is the system bandwidth capacity and $b_{k,N}$ is the bandwidth requirement of a new service-class k call.

We denote by c the total number of occupied b.u. at an instant and by j the total number of b.u. that would be occupied if all users were *active*. The parameter j at a given moment is considered as the system state.

We also denote by $q(j)$ the probability of the state j. The *bandwidth occupancy*, $\Lambda(c \mid j)$, is defined as the conditional probability that c b.u. are occupied in state j and can be calculated from (25) recursively:

$$\begin{aligned}\Lambda(c \mid j) = &\sum_{k=1}^{K} P_{k,N}(j)[v_k \Lambda(c-b_{k,N} \mid j-b_{k,N}) + (1-v_k)\Lambda(c \mid j-b_{k,N})] \\ &+ \sum_{k=1}^{K} P_{k,H}(j)[v_k \Lambda(c-b_{k,H} \mid j-b_{k,H}) + (1-v_k)\Lambda(c \mid j-b_{k,H})],\end{aligned} \tag{25}$$

for $j = 1,...,j_{\max}$ and $c \le j$

where $j_{\max}$ is the max. system state, $\Lambda(0|0)$=1 and $\Lambda(c|j)$=0 for $c>j$.

In CDMA systems, due to the *inter-cell interference*, blocking of a service-class k call may occur at any state j with a probability $LB_{k,N}(j)$. This probability is given by summing over c the LBPs multiplied by the corresponding bandwidth occupancies:

$$LB_{k,N}(j) = \sum_{c=0}^{j} \beta_{k,N}(c)\Lambda(c \mid j) \tag{26}$$

The service-class k *bandwidth share* in state j, $P_{k,N}(j)$ and $P_{k,H}(j)$, can be derived from (27) and (28) for new and handoff calls, respectively.

$$P_{k,N}(j) = \frac{\alpha_{k,N}(1 - LB_{k,N}(j - b_{k,N}))b_{k,N}q(j - b_{k,N})}{jq(j)} \tag{27}$$

$$P_{k,H}(j) = \frac{\alpha_{k,H}(1 - LB_{k,H}(j - b_{k,H}))b_{k,H}q(j - b_{k,H})}{jq(j)} \tag{28}$$

The un-normalized *state probabilities* are given by extending the K-R recursion due to the presence of local blockings:

$$\begin{aligned}\hat{q}(j) = &\frac{1}{j}\sum_{k=1}^{K} \alpha_{k,H}(1 - L_{k,H}(j - b_{k,H}))b_{k,H}\delta_k(j)\hat{q}(j - b_{k,H}) + \\ &\frac{1}{j}\sum_{k=1}^{K} \alpha_{kc,H}(1 - L_{k,H}(j - b_{kc,H}))b_{kc,H}\delta_{kc}(j)\hat{q}(j - b_{kc,H}) + \\ &\frac{1}{j}\sum_{k=1}^{K} \alpha_{k,N}(1 - L_{k,N}(j - b_{k,N}))b_{k,N}\hat{q}(j - b_{k,N}),\end{aligned} \tag{29}$$

for $j = 1,..., j_{\max}$

where $\hat{q}(0)$=1, $\hat{q}(j)$=0 for j<0 and the parameters $\delta_{k,H}(j), \delta_{kc,H}(j)$ are given by (30) and (31), respectively.

$$\delta_k(j) = \begin{cases} 1, & \text{when } 1 \le j \le C \text{ and } b_{kc} = 0 \\ 1, & \text{when } j \le J_k + b_k \text{ and } b_{kc} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{30}$$

$$\delta_{kc}(j) = \begin{cases} 1, & \text{when } (b_k \ge j > J_k + b_{kc}) \text{ and } (b_{kc} > 0) \\ 0, & \text{otherwise} \end{cases} \tag{31}$$

The threshold J_k is used for the selection of the bandwidth requirement of an arriving service-class k handoff call. In particular, if $j > J_k$, then the requested bandwidth is $b_{k,H}$; if $j \le J_k$, then the requested bandwidth is $b_{kc,H}$.

Finally, the normalized *state probabilities*, $q(j)$, are given by:

$$q(j) = \frac{\hat{q}(j)}{\sum_{j=0}^{j_{\max}} \hat{q}(j)} \tag{32}$$

B. *Call Blocking Probabilities*

The new-call blocking probabilities of service-class k can be calculated by adding all the *state probabilities* multiplied by the corresponding LBFs:

$$B_{k,N} = \sum_{j=0}^{j_{\max}} q(j)LB_{k,N}(j) \tag{33}$$

For the calculation of the *handoff-call* blocking probability, $B_{k,H}$, we must take into account the threshold J_k and thus incorporate the parameter $\gamma_k(j)$, defined as:

$$\gamma_k(j) = \begin{cases} 1, & \text{when } j \le J_k \\ 0, & \text{otherwise} \end{cases} \tag{34}$$

Hence, the *handoff-call* blocking probability of service-class k is given by:

$$B_{k,H} = \sum_{j=0}^{j_{\max}} q(j)\gamma_k(j)LB_{k,H}(j) \quad (35)$$

VI. PERFORMANCE EVALUATION

In this section, we compare the analytical versus simulation results in respect of call blocking probabilities. The simulation language used is Simscript III [25]. We present analytical and simulation results for both types of calls, new and handoff. Simulation results are mean values of 10 runs with 95% confidence interval. The resultant reliability ranges of the simulation measurements are very small and, therefore, we present only mean values.

We evaluate two different service-classes with the following parameters:

a) $R_1 = 144\,Kbps, (E_b / N_0)_1 = 3\,dB$, and $v_1 = 0.67$.

b) $R_{2,1} = 384\,Kbps, R_{2,2} = 320\,Kbps,\ (E_b / N_0)_2 = 4\,dB$, $J_1 = 0.6$ and $v_2 = 1$.

We assume that the inter-cell interference is lognormally distributed with mean $E[I_{inter}] = 2*E-18\,mW$ and coefficient of variation $CV[I_{inter}] = 1$. The thermal noise power density is $-174\,dBm/Hz$. For discretization we use $g = 0.001$. The following cell load thresholds are considered: $n_H = n_{\max} = 0.8$ and $n_N = 0.75$, for new and handoff calls, respectively. We generate traffic load according to the Table I. That is, in the case of the 1st service-class the traffic-load point 1 corresponds to $a_{1,N} = 1.0$ erl and $a_{1,H} = 0.1$ erl for the new and handoff calls, respectively.

In Figs. 1 and 2, we present the analytical and simulation call blocking probabilities for the 1st and the 2nd service-class, respectively. We observe that the accuracy of the proposed model is very good, since the analytical results are very close to simulation results in all cases. We also observe that by using different cell load thresholds for new and handoff calls ($n_N > n_H$), we achieve lower blocking probabilities for the handoff calls.

TABLE I. OFFERED TRAFFIC (ERL).

	1	2	3	4	5	6
$a_{1,N}$	1.0	1.25	1.5	1.75	2.0	2.25
$a_{1,H}$	0.1	0.2	0.3	0.4	0.5	0.6
$a_{2,N}$	0.2	0.3	0.4	0.5	0.6	0.7
$a_{2,H}$	0.05	0.1	0.15	0.2	0.25	0.3

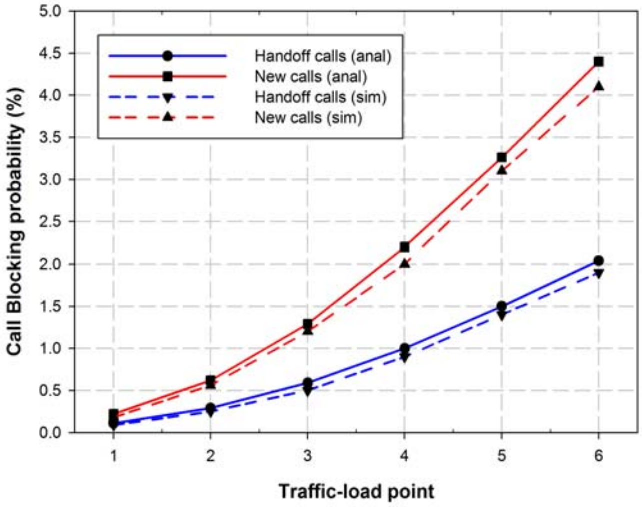

Figure 1. Call blocking probabilities for new and handoff calls vs offered traffic-load (1st service-class).

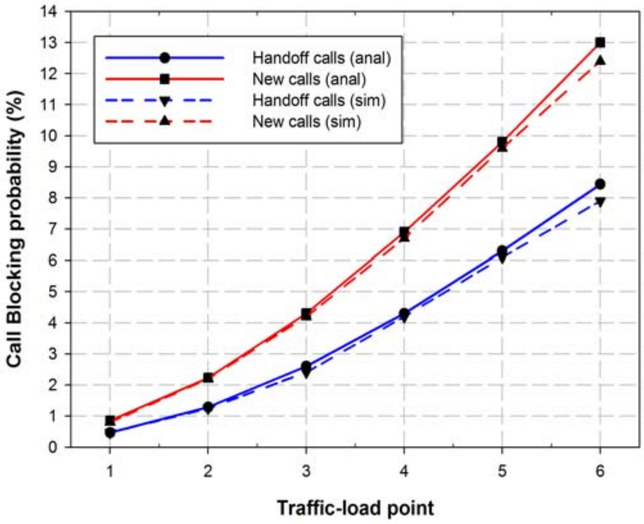

Figure 2. Call blocking probabilities for new and handoff calls vs offered traffic-load (2nd service-class).

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented a new teletraffic model for the analysis of handoff traffic in cellular CDMA systems. The proposed approach is based on a single-threshold model that allows the handoff call request less bandwidth when the system is overloaded. In that case, the handoff-call blocking probability can be reduced. We have performed simulation studies, which show that the accuracy of our proposed analytical model is very satisfactory. As a future work, we will study the impact of multiple thresholds on the blocking probabilities of handoff calls. Also, we will incorporate a finite number of traffic sources into our model.

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