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Cross-Layer Resource Allocation for Variable Bit Rate Multiclass Services in a Multirate Multicarrier DS-CDMA Network

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An approximate analytical formulation of the resource allocation problem for handling *variable bit rate multiclass* services in a cellular round-robin carrier-hopping multirate multicarrier direct-sequence code-division multiple-access (MC-DS-CDMA) system is presented. In this paper, all grade-of-service (GoS) or quality-of-service (QoS) requirements at the connection level, packet level, and link layer are satisfied *simultaneously* in the system, instead of being satisfied at the connection level or at the link layer only. The analytical formulation shows how the GoS/QoS in the different layers are intertwined across the layers. A novelty of this paper is that the outages in the subcarriers are minimized by spreading the subcarriers' signal-to-interference ratio evenly among all the subcarriers by using a dynamic round-robin carrier-hopping allocation scheme. A complete sharing (CS) scheme with guard capacity is used for the resource sharing policy at the connection level based on the mean rates of the connections. Numerical results illustrate that significant gain in the system utilization is achieved through the joint coupling of connection/packet levels and link layer.

Keywords and phrases: bit error rate, outage probability, variable bit rate multiclass services, round-robin carrier hopping, multirate multicarrier DS-CDMA, cross-layer coupling.

1. INTRODUCTION

Connection-level resource allocation typically has new connection and handoff connection blocking probabilities, and forced termination probability of handoff connections as grade-of-service (GoS) measures. These system connections' GoS metrics are collectively defined at the *connection level*. When traffic flows are admitted into the system, quality of service (QoS) is measured in terms of packet loss rate and/or packet delay. These packets' QoS metrics are collectively defined at the *packet level*. Scheduling and *statistical multiplexing gains* play an important role in determining the amount of traffic that can be admitted into the system while still satisfying the packet-level QoS. Satisfying the connection-level GoS constraints alone may limit the packet-level traffic load that can potentially be admitted into the system. Higher system utilization can be achieved by making use of both the connection-level and packet-level characteristics [1]. To our knowledge, Cheung and Mark [1] were the first to propose a resource allocation strategy in a cellular network subject to joint packet/connection-level GoS/QoS constraints to improve system performance for a single-class traffic. In [2], Wong et al. considered a complete sharing scheme with K classes in their numerical results. Improvements in system utilization with joint coupling of connection/packet-levels are found in these papers.

Successful packet transmissions in a cellular system depends on the total interference in the system. The channel outage QoS metric is defined at the *link layer*. The idea of joint coupling of connection/packet-levels is extended to include the link layer in order to maximize system utilization for a multirate direct-sequence code-division multiple-access (DS-CDMA) system using *cross-layer* designs in [3, 4]. The analytical formulations in [3, 4] are based on a single-carrier multirate DS-CDMA system with on/off and Maglaris' variable bit rate (VBR) sources [5], respectively. Maglaris' model is suitable for video or other multirate traffic.

Recently, multicarrier (MC-) CDMA systems have been receiving a lot of attention as they can promise high data rate required by 4G mobile cellular systems, and they are effective in mitigating multipath fading and rejecting narrowband interference [6, 7, 8, 9, 10]. From a physical point of view, MC systems can also offer frequency diversity. Thus, MC-CDMA is one of the candidates for 4G cellular multimedia networks. In this paper, the performance of the cross-layer coupling in the uplink of a novel round-robin carrier-hopping multirate MC-DS-CDMA system with Maglaris' VBR traffic is derived. A novelty of this paper is that the outages in the subcarriers are minimized by spreading the subcarriers' signal-to-interference ratio (SIR) evenly among all the subcarriers by using a dynamic round-robin carrier-hopping allocation scheme. This will also help to increase the number of users that can be supported in the system. To the best of our knowledge, this way of evenly distributing the SIR among all the subcarriers is new. The current work utilizes and adapts the analytical model in [3] to analyze cross-layer resource allocation for a round-robin carrier-hopping multirate MC-DS-CDMA.

The rest of the paper is organized as follows. In Section 2, we describe the system model and system parameters in an MC-DS-CDMA system. In Section 3, we describe the problem that this paper will address. Section 4 presents a novel round-robin carrier-hopping multirate MC-DS-CDMA system. In Section 5, we present an analytical model for *VBR multiclass* services at the connection level, packet-level and link layer in the round-robin carrier-hopping multirate MC-DS-CDMA system. Section 6 presents numerical results for three classes from the analysis presented in Section 4. Finally, concluding remarks are made in Section 7.

2. SYSTEM MODEL

We consider a typical generic radio cell with physical capacity C in a cellular arrangement. For easy reference, we define the basic unit of capacity as a *channel*. A user of some traffic class may transmit at a rate equal to one channel, while other transmission rates may require multiple channels. The cell-site (base station) supports K classes of services that can originate from mobile users in the cell. The generic cell is characterized by the following system parameters used throughout the paper.

System-level parameters

(i) C: total physical capacity in a cell.
(ii) K: total number of traffic classes.
(iii) N_c: number of subcarriers.
(iv) r_k: number of equivalent basic channels (units) required by each class k connection's spreading code in a subcarrier.
(v) M_k: maximum number of active spreading codes used by each class k connection in the active subcarriers.
(vi) $\mathcal{N} > C$: total nominal capacity in a cell (capitalizing on statistical multiplexing gain).

The dynamics of a radio cell are driven by new connection requests, connection terminations, and handoffs induced by user mobility. Since maintaining an ongoing connection is more important than admitting a new connection, handoff connections are given a higher access priority. One way to facilitate this is to reserve capacity for admitting handoff connections, which is not accessible by new requests. The reserved capacity is sometimes referred to as *guard capacity*.

Let C_G and C_i denote, respectively, the guard capacity and the instantaneous capacity occupancy plus the new or handoff connection capacity. We have the following.

Admission rule

(1) Admit both new and handoff connections if $\mathcal{N} - C_i \geq C_G$, where $(\mathcal{N} - C_i)$ is the free capacity left after admitting a new or handoff connection.
(2) Admit only handoff connections if $0 \leq \mathcal{N} - C_i < C_G$, where $(\mathcal{N} - C_i)$ is the free capacity left after admitting a handoff connection.

Deployment of the guard capacity policy has the following ramifications.

(i) A handoff connection is accepted as long as there is enough *capacity* available.
(ii) A new connection is accepted as long as the available capacity (if it is admitted) is greater than C_G.

In a CDMA-based system, system capacity is a soft quantity which is determined by the SIR specification, corresponding to the target bit error rate (BER) at the link layer. This is the reason that we refer to $\mathcal{N}$ as the nominal capacity. The connection level, packet-level, and link layer have different but related performance measures. Specifically, the connection-level performance is measured in terms of blocking probabilities (GoS); the packet-level performance is measured in terms of packet loss rate (QoS); and the link layer performance is measured in terms of SIR or outage probability.

3. PROBLEM STATEMENT

Consider a class k connection. Its GoS/QoS is specified by the new connection blocking probability B_{nk}, handoff connection blocking probability B_{hk}, and system utilization N_{uk} at the connection level; the packet loss probability L_k at the packet-level; and the outage probability $P_{\text{outage},k}$ at the link layer. The goal is to maximize the system utilization or nominal capacity under these GoS/QoS requirements.

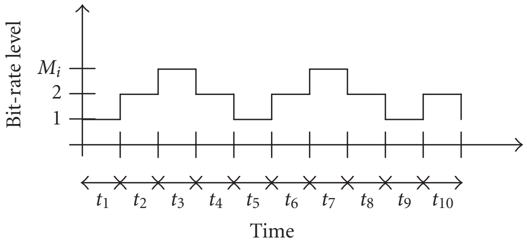

Figure 1: A VBR source.

4. ROUND-ROBIN CARRIER-HOPPING MULTIRATE MC-DS-CDMA

A single-carrier DS-CDMA system has a spread-spectrum bandwidth of W at a center frequency of f, while a multicarrier DS-CDMA system has a spread-spectrum bandwidth of W/N_c at frequency f_c in each of its subcarriers, where N_c is the number of subcarriers and $c = 1, 2, \ldots, N_c$. The same spreading code can be used in each of the subcarriers for a user.

Figure 1 shows a VBR source with discrete bit rate levels. Each level has a bit-rate of R_i, where $i = 1, 2, \ldots, K$ and K is the number of traffic classes. The highest level is M_i and it has a bit rate of M_iR_i. Each level of bit rate is transmitted through one subcarrier. Thus, a VBR source is transmitted through a number of subcarriers, each using the same spreading code. In each subcarrier, there can be different classes of users, each transmitting at different bit rates R_i. Every user in the same class transmits at the same bit rate in each of the subcarriers that they are transmitting in. For ease of illustration, the time durations for a source at each level are shown equal. To evenly spread the usage of the subcarriers and outage probabilities in the subcarriers and to increase the number of users in the system, we propose to use a novel round-robin carrier-hopping multirate MC-DS-CDMA scheme. The usage of the subcarriers is shown in Table 1. The symbol ô represents that a reference subcarrier is used, while the symbol o represents that the subsequent subcarrier is used. This round-robin carrier-hopping carrier allocation scheme works as follows. The reference subcarrier is moved in a round-robin manner over all the subcarriers. Table 1 shows that the goal of evenly spreading the usage of the subcarriers is achieved. Thus, the outage probabilities in the subcarriers are lowered and the number of users that can be supported is increased.

Note that a round-robin carrier-hopping scheme is easier to implement than a random carrier-hopping scheme.

5. ANALYTICAL MODEL

5.1. Connection level

Consider a K-class complete sharing (CS) model. The guard capacity C_G is reserved for handoff connections only. To facilitate analytical modeling, it is necessary to make certain assumptions about the traffic parameters. It is not unreasonable to assume that the holding time has a negative exponential distribution [11]. Although a negative exponential distribution assumption may not be as reasonable for the cell-dwell time, for analytical tractability, we will make the same assumption for cell-dwell time (interhandoff time) [11] and model the channel occupancy as a K-dimensional Markov chain with the connection-level parameters in Section 3. This Markov chain can be modeled and solved using the techniques in [12].

Table 1: Subcarriers used for a VBR source in a round-robin carrier-hopping MC-DS-CDMA system.

Time epoch	Subcarrier used				
	1	2	3	4	N_c
t_1	ô	—	—	—	—
t_2	—	ô	o	—	—
t_3	—	—	ô	o	o
t_4	—	—	—	ô	o
t_5	—	—	—	—	ô
t_6	ô	o	—	—	—
t_7	—	ô	o	o	—
t_8	—	—	ô	o	—
t_9	—	—	—	ô	—
t_{10}	o	—	—	—	ô

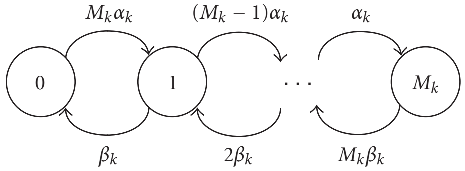

Figure 2: Continuous-time Markov chain for a single VBR source.

The connection-level GoS is dependent on the packet-level QoS. Thus we need to understand the packet-level characteristics before solving for the connection-level GoS. We assume that a class k connection, after being admitted into the system, behaves according to Maglaris' model [5]. From Maglaris' model [5], a VBR source can be modeled by a continuous-time Markov chain with finite states as shown in Figure 2.

Each state m_k represents the discrete level of bit rates generated by a single source. The combined data rate of each source is m_kR_k, where R_k is the bit rate for user k using one spreading code in the subcarrier. That is, we assume that each level of bit rate uses one spreading code in one subcarrier for a class k user. This means that each level has a data rate of R_k corresponding to one class k spreading code. Users use the same spreading code in their subcarriers. Each low-bit-rate level is modeled by a two-state mini-source with an increase rate of α_k and a decrease rate of β_k. Thus the continuous-time MC for a single VBR source at state m_k has an increase rate of $(M_k - m_k)\alpha_k$ and a decrease rate of $m_k\beta_k$, where M_k is the highest-level bit rate, and this is also the maximum number of active spreading codes used in M_k subcarrier by a class k user. If $M_k = 1$, the source is an *on/off* source.

The steady-state probability of being in state m_k, denoted by P_{m_k}, is given by

$$P_{m_k} = \binom{M_k}{m_k} (p_k)^{m_k} (1 - p_k)^{M_k - m_k}, \quad m_k = 0, 1, 2, \dots, M_k, \tag{1}$$

where $p_k = \alpha_k/(\alpha_k + \beta_k)$.

Analytical techniques such as those in [12] can be used to solve for the connection-level GoS like blocking probabilities and system utilization. To this end, let $\mathbf{n} = (n_1, n_2, \dots, n_K)$ denote the state of the system with the number of users (n_k) in each of the K classes, let $\mathbf{r} = (r_l, r_l, \dots, r_l)$ denote the number of basic subcarrier channels (r_k) required for each class k connection's spreading code in the subcarriers, and let $\overline{\mathbf{m}} = \{\overline{m}_1, \overline{m}_2, \dots, \overline{m}_K\}$ denote the mean number of active subcarrier spreading codes used by each class k connection in the active subcarriers, where $\overline{m}_k = M_k\alpha_k/(\alpha_k + \beta_k)$. Let $\lambda_k(\mathbf{n})$ denote the arrival rate and $\mu_k(\mathbf{n})$ the departure rate in the system. The state space of the system, denoted by S, is given by $S := \{\mathbf{n} : (\overline{\mathbf{m}} \cdot \mathbf{r}) \cdot \mathbf{n} \le \mathcal{N}\}$.

When the system is in state $\mathbf{n}$ and a class k connection (new or handoff) arrives, an admission policy determines whether or not the connection is admitted into the system. Here, the admission policy is a complete sharing scheme with guard capacity. We can specify the admission policy by mapping $\mathbf{f} := (f_1, \dots, f_K)$ for new and handoff connections, $\mathbf{f}_G := (f_{G1}, \dots, f_{GK})$ for handoff connections, where f_k and $f_{Gk} : S \to \{0, 1\}$, and $f_k(\mathbf{n})$ and $f_{Gk}(\mathbf{n})$ each takes on the value 0 or 1 if a class k connection is rejected or admitted, respectively, when the system state is $\mathbf{n}$. These mappings are defined by the following equations:

$$\begin{gathered} f_k(\mathbf{n}) = \begin{cases} 1, & \overline{\mathbf{m}} \cdot \mathbf{r} \cdot \mathbf{n} + \overline{m}_k r_k \le \mathcal{N} - C_G, \\ 0 & \text{otherwise}, \end{cases} \\ f_{Gk}(\mathbf{n}) = \begin{cases} 1, & \mathcal{N} - C_G < \overline{\mathbf{m}} \cdot \mathbf{r} \cdot \mathbf{n} + \overline{m}_k r_k \le \mathcal{N}, \\ 0 & \text{otherwise}, \end{cases} \end{gathered} \tag{2}$$

for which $S(\mathbf{f}) + S(\mathbf{f}_G) = S$.

Let $P(\mathbf{n})$ denote the equilibrium probability that the system is in state $\mathbf{n}$. The global balance equations for the Markov process under the policies $\mathbf{f}$ and $\mathbf{f}_G$ are

$$\begin{aligned} &\sum_{k=1}^{K} \left[\lambda_k(\mathbf{n})\{f_k(\mathbf{n}) + f_{Gk}(\mathbf{n})\} + \mu_k(\mathbf{n})\right] P(\mathbf{n}) \\ &\quad = \sum_{k=1}^{K} P(\mathbf{n} - \mathbf{e}_k)\lambda_k(\mathbf{n} - \mathbf{e}_k) \times \{f_k(\mathbf{n} - \mathbf{e}_k) + f_{Gk}(\mathbf{n} - \mathbf{e}_k)\} \\ &\qquad + \sum_{k=1}^{K} P(\mathbf{n} + \mathbf{e}_k)\mu_k(\mathbf{n} + \mathbf{e}_k), \quad \mathbf{n} \in S, \end{aligned} \tag{3}$$

where $\mathbf{e}_k$ is a K-dimensional vector of all zeros except for a one in the kth place,

$$\lambda_k(\mathbf{n}) = \begin{cases} \lambda_{nk} + \lambda_{hk} & \text{if } f_k(\mathbf{n}) = 1, \\ \lambda_{hk} & \text{if } f_{Gk}(\mathbf{n}) = 1, \end{cases} \tag{4}$$

$$\mu_k(\mathbf{n}) = n_k(\mu_{ck} + \mu_{hk}), \quad 0 < \overline{\mathbf{m}} \cdot \mathbf{r} \cdot \mathbf{n} \le \mathcal{N}. \tag{5}$$

λ_{nk} is the arrival rate of class k new connections, λ_{hk} is the arrival rate of class k handoff connections, $1/\mu_{ck}$ is the mean connection holding time or lifetime of a class k connection, and $1/\mu_{hk}$ is the mean dwell time of a class k connection. The first condition in (4) allows both new and handoff connections to be admitted to $(\mathcal{N} - C_G)$ channels, while the second condition allows only handoff connections to be admitted to C_G channels. Equation (5) allows both new and handoff connections to be serviced when the total channel occupancy is less than or equal to N basic channels. Due to the memoryless property of the exponential distribution, the distribution of the remaining connection holding time is the same as the distribution of the original connection holding time. The departure of a connection from the cell depends on the minimum of its cell-dwell time and its remaining connection holding time. Equation (3) can be solved using LU decomposition [13] together with the condition for the total probability of all states to obtain $P(\mathbf{n})$. LU decomposition is a common numerical technique for solving linear algebraic equations. This gives exact solution. However, an efficient approximate computational algorithm [11] can be used for a large system state space. Results can be precomputed and stored in a lookup table for real-time applications in this situation.

Let θ_{nk} denote the probability that the next arrival is a new class k connection. Then $\theta_{nk} = \lambda_{nk}/\sum_{k=1}^{K}\lambda_k$. Similarly, if θ_{hk} denotes the probability that the next arrival is a class k handoff connection, we have $\theta_{hk} = \lambda_{hk}/\sum_{k=1}^{K}\lambda_k$, and if θ_k denotes the probability that the next arrival is a class k connection, we have $\theta_k = \lambda_k/\sum_{k=1}^{K}\lambda_k$. A new class k connection is blocked from entering the system (and is assumed lost) if upon arrival, it finds that it cannot be accommodated because the available *basic channel capacity* (excluding the guard capacity) is less than $\overline{m}_k r_k$. Therefore the blocking probability for a new class k connection considering all classes is given by

$$\begin{gathered} B_{nk} = \sum_{n_1=0}^{N_1} \sum_{n_2=0}^{N_2} \cdots \sum_{n_K=0}^{N_K} P(n_1, n_2, \dots, n_K)\theta_{nk}, \\ \left(\mathcal{N} - C_G - \sum_{i=1}^{K} n_i \overline{m}_i r_i\right) < \overline{m}_k r_k, \end{gathered} \tag{6}$$

where $N_k = \lceil(\mathcal{N} - \sum_{i=1}^{k-1} n_i \overline{m}_i r_i)/(\overline{m}_k r_k)\rceil$ and the K summations with maximum limits of N_k's define the system state space $S := \{\mathbf{n} : \overline{\mathbf{m}} \cdot \mathbf{r} \cdot \mathbf{n} \le \mathcal{N}\}$. A class k handoff connection is blocked from entering the system (and is assumed lost) if upon arrival, it finds that it cannot be accommodated because the available basic channel capacity is less than $\overline{m}_k r_k$ (including the guard capacity). Therefore the blocking probability for a class k handoff connection considering all classes is given by

$$\begin{aligned} B_{hk} &= \sum_{n_1=0}^{N_1}\sum_{n_2=0}^{N_2}\cdots\sum_{n_K=0}^{N_K} P(n_1,n_2,\ldots,n_K)\theta_{hk}, \\ &\left(\mathcal{N} - \sum_{i=1}^{K} n_i\overline{m}_i r_i\right) < \overline{m}_k r_k. \end{aligned} \tag{7}$$

The blocking probabilities of new and handoff connections, denoted by B_n and B_h, respectively, are given by $B_n = \sum_{k=1}^{K} B_{nk}$ and $B_h = \sum_{k=1}^{K} B_{hk}$. Summing B_n and B_h yields the total blocking probability, $B = B_n + B_h$. The system utilization, defined as the number of basic rate users that can be supported, for class k connections is given by

$$N_{uk} = \sum_{n_1=0}^{N_1}\sum_{n_2=0}^{N_2}\cdots\sum_{n_K=0}^{N_K} P(n_1,n_2,\ldots,n_K)n_k\overline{m}_k r_k. \tag{8}$$

The total system utilization is $N_u = \sum_{k=1}^{K} N_{uk}$. From [2], invoking Little's law for a generic cell, the class k handoff connection arrival rate can be approximated under low blocking probabilities as follows:

$$\lambda_{hk} = \frac{\mu_{hk}\lambda_{nk}}{\mu_{ck}}, \tag{9}$$

where $1/\mu_{hk}$ is the mean dwell time of a class k connection, λ_{nk} is the arrival rate of class k new connections, and $1/\mu_{ck}$ is the mean connection holding time of a class k connection.

Let n_k be the number of active class k connections. Using the definition of marginal distribution, the pmf of n_k, denoted by $P(n_k)$, is given by

$$\begin{aligned} &P(n_k) \\ &\quad = \sum_{n_1=0}^{N_1}\cdots\sum_{n_{k-1}=0}^{N_{k-1}}\sum_{n_{k+1}=0}^{N_{k+1}}\cdots\sum_{n_K=0}^{N_K} P(n_1,\ldots,n_{k-1},n_k,n_{k+1},\ldots,n_K), \end{aligned} \tag{10}$$

where $n_k = 0,1,\ldots,n_{k,\max}$ and $n_{k,\max} = \lceil \mathcal{N}/(\overline{m}_k r_k)\rceil$. Thus the mean, second moment and variance of n_k, denoted by $\overline{n}_k$, $\overline{n_k^2}$ and $\mathrm{Var}[n_k]$, are, respectively, given by $\overline{n}_k = \sum_{n_k=0}^{n_{k,\max}} n_k P(n_k)$, $\overline{n_k^2} = \sum_{n_k=0}^{n_{k,\max}} n_k^2 P(n_k)$, and $\mathrm{Var}[n_k] = \overline{n_k^2} - (\overline{n}_k)^2$.

The connection admission used here at the connection level is based on $\overline{\mathbf{m}}$ which is based on the mean rate of a connection. Nevertheless, the joint QoS coupling for the connection level, packet level, and link layer using CDMA inherently achieves statistical multiplexing and assures that all GoS/QoS requirements at the connection level, packet level, and link layer are satisfied simultaneously.

5.2. *Packet level*

We consider a subcarrier, assuming that all subcarriers are statistically identical. This assumption is valid as a round-robin carrier-hopping carrier allocation scheme is used. The probability that subcarrier c is used for transmission, given that the source is in state m_k, denoted by $P_{c|m_k}$, is given by

$$P_{c|m_k} = \frac{m_k}{N_c}, \quad m_k = 0,1,2,\ldots,M_k,\ c = 1,2,\ldots,N_c, \quad M_k \leq N_c. \tag{11}$$

Unconditioning the dependence on state m_k, using (1) and (11), and simplifying, the probability that subcarrier c is used for transmission, denoted by P_c, is given by

$$P_c = \sum_{m_k=0}^{M_k} P_{c|m_k}P_{mk} = \frac{M_k p_k}{N_c}, \quad M_k \leq N_c. \tag{12}$$

Note that if $M_k = 1$, the source is an on/off source and the probability that subcarrier c is used for transmission is simply equal to the source activity factor p_i divided by the number of subcarriers N_c. This is due to the round-robin carrier-hopping allocation scheme used. This allocation scheme evenly spreads the subcarriers' usage by a source.

Treating each subcarrier as *orthogonal* from other subcarriers, we can model each subcarrier as though it has on/off multiclass traffic with the multirate MC-DS-CDMA sources' subcarrier activity factors being treated like the on/off sources' activity factors. Thus we can make use of the results in [3].

The probability that an active spreading code in a subcarrier is used by source k, denoted by $\Pr[\psi_k = 1] = q_k$, is given by

$$\Pr[\psi_k = 1] = q_k = P_c, \quad k = 1,2,\ldots,K. \tag{13}$$

The first and second moments, and the variances of the active class k spreading code used, x_k, in a subcarrier are, respectively, given by $\overline{x_k} = q_k$, $\overline{x_k^2} = q_k$ and $\mathrm{Var}[x_k] = q_k(1-q_k)$. For a stationary admission control policy, the underlying process is Markovian. Let

(i) $r_k = R_k/R$, where R is the basic data rate, be the number of basic channels a class k connection needs to transmit its packets for each of its spreading codes in a subcarrier;
(ii) n_k be the number of class k connections in progress;
(iii) l_k be the number of active spreading codes used by n_k class k connections in a subcarrier;

n_k and l_k together characterize the state space, with the state descriptor given by

$$(\mathbf{n},\mathbf{l}) = (n_1,\ldots,n_K;l_1,\ldots,l_K). \tag{14}$$

The probability that l_k active spreading codes are used in a subcarrier, given that there are n_k connections in progress, is given by

$$P(l_k|n_k) = \binom{n_k}{l_k} q_k^{l_k}(1-q_k)^{n_k-l_k}, \quad l_k = 0,1,\ldots,n_k. \tag{15}$$

Assuming one packet is transmitted in a basic channel and *no packet buffer*, the equivalent class k packet loss probability normalized over all classes for the CS scheme is given by

$$\begin{aligned} L_k &= \frac{1}{L_{\text{sum}}} \\ &\quad\times\Bigg[\sum_{n_1=0}^{N_1}\sum_{n_2=0}^{N_2}\cdots\sum_{n_K=0}^{N_K} P(n_1,n_2,\ldots,n_K) \\ &\qquad\times\sum_{l_1=0}^{n_1}\sum_{l_2=0}^{n_2}\cdots\sum_{l_K=0}^{n_K} P(l_1\mid n_1)P(l_2\mid n_2)\cdots P(l_K\mid n_K) \\ &\qquad\times(l_k r_k)P_{\text{outage},k}\Bigg], \end{aligned} \tag{16}$$

where

$$\begin{aligned} L_{\text{sum}} &= \sum_{n_1=0}^{N_1}\sum_{n_2=0}^{N_2}\cdots\sum_{n_K=0}^{N_K} P(n_1,n_2,\ldots,n_K) \\ &\quad\times\sum_{l_1=0}^{n_1}\sum_{l_2=0}^{n_2}\cdots\sum_{l_K=0}^{n_K} \times P(l_1\mid n_1)P(l_2\mid n_2)\cdots P(l_K\mid n_K) \\ &\quad\times\sum_{i=1}^{K}(l_i r_i), \end{aligned} \tag{17}$$

and $P_{\text{outage},k}$ is the outage probability for class k connections which is defined in (18). The total packet loss probability is given by $L = \sum_{k=1}^{K} L_k$.

5.3. Link layer

To solve for the link layer QoS of outage probability in a subcarrier, the first and second moments, and the variance of the required energy-to-interference density ratio $(E_b/I_0)_k$ for each class k connection in the subcarrier are required. Let ε_k denote the required energy-to-interference density ratio $(E_b/I_0)_k$ for each class k connection in the subcarrier under some propagation conditions. Assuming that the class k signal emerging from the propagation channel in the subcarrier is lognormal distributed with a normal mean of t_k and a normal variance of σ_k^2. The mean and second moment of ε_k are, respectively, given by $\overline{\varepsilon}_k = \exp((\beta\sigma_k)^2/2 + \beta t_k)$, and $\overline{\varepsilon_k^2} = \exp(2(\beta\sigma_k)^2 + 2\beta t_k)$, where $\beta = (\ln 10)/10$. Its variance is thus $\operatorname{Var}[\varepsilon_k] = \exp(2(\beta\sigma_k)^2 + 2\beta t_k) - \exp((\beta\sigma_k)^2 + 2\beta t_k)$.

We consider the uplink capacity focusing on a subcarrier assuming statistically identical subcarriers and define the outage to occur when the total influence of the users, both intracell and intercell, introduces an amount of interference density I_0 so great that it exceeds the background noise level N_0 by an amount $I_0/N_0 = 1/\eta$ in a subcarrier. Applying the approach in [3] to a subcarrier, the class i outage probability in a subcarrier $P_{\text{outage},i}$ for MC-DS-CDMA can be written as

$$P_{\text{outage},i} \approx Q\left(\frac{[((W/N_c)/R_i)(1-\eta) - \operatorname{E}[Z_i]]}{\sqrt{\operatorname{Var}[Z_i]}}\right), \tag{18}$$

where

$$\begin{aligned} &\operatorname{E}[Z_i] \\ &\quad= \left[\begin{aligned} &\overline{n}_i q_i \exp\left(\frac{(\beta\sigma_i)^2}{2} + \beta t_i\right) \\ &\quad+ \sum_{k=1,\,k\neq i}^{K} \overline{n}_k q_k \left(\frac{R_k}{R_i}\right)\times\exp\left(\frac{(\beta\sigma_k)^2}{2} + \beta t_k\right) \end{aligned}\right](1+f), \\ &\operatorname{Var}[Z_i] \\ &\quad= \left[\begin{aligned} &\overline{n_i^2} q_i \exp\left(2(\beta\sigma_i)^2 + 2\beta t_i\right) - (\overline{n}_i)^2 q_i^2 \exp\left((\beta\sigma_i)^2 + 2\beta t_i\right) \\ &\quad+ \sum_{k=1,\,k\neq i}^{K} \overline{n_k^2} q_k \left(\frac{R_k^2}{R_i^2}\right)\exp\left(2(\beta\sigma_k)^2 + 2\beta t_k\right) \\ &\quad- \sum_{k=1,\,k\neq i}^{K} (\overline{n}_k)^2 q_k^2 \left(\frac{R_k^2}{R_i^2}\right)\exp\left((\beta\sigma_k)^2 + 2\beta t_k\right) \end{aligned}\right] \\ &\qquad\times(1+f), \end{aligned} \tag{19}$$

$Q(y) = \int_y^\infty e^{-x^2/2}dx/\sqrt{2\pi}$, R_i is the data rate of class i's spreading code in the subcarrier, W/N_c is the spread-spectrum bandwidth in the subcarrier, and f is the other cell to own the cell relative interference factor in a subcarrier. Clearly, from (18) and (19), the link layer class i outage probability in a subcarrier is a function of not just the link layer characteristics (σ_k, t_k) of the required energy-to-interference density ratios, but also a function of the connection-level characteristics (n_k) of the number of users of different classes as well as a function of the packet-level characteristics (M_k, p_k) of the VBR sources and the number of subcarriers (N_c). Note that $q_k = M_k p_k/N_c$.

For the purpose of assessing the performance of the uncoupled connection-level, packet-level, and link-layer approach, we will assume that the nominal capacity $\mathcal{N}$ without coupling is given by

$$\begin{aligned} \mathcal{N} = \max[&n_{1,\text{maxi}}(\overline{m}_1 r_1), n_{2,\text{maxi}}(\overline{m}_2 r_2), \ldots, \\ &n_{K,\text{maxi}}(\overline{m}_K r_K)], \end{aligned} \tag{20}$$

where $n_{k,\text{maxi}} = (((W/N_c)/R_k)/\overline{\varepsilon}_k)((1-\eta)/(1+f))$.

5.4. Joint connection-level, packet-level, and link-layer QoS coupling

We can maximize the system utilization through coupling of the connection-level, packet-level, and link-layer parameters. This is also equivalent to maximizing the nominal capacity $\mathcal{N}$. The maximization can be achieved by solving the coupling problem

$$\max\{N_u\} \quad \text{or} \quad \max\{\mathcal{N}\} \tag{21}$$

subject to the constraints

$$B_{nk} \le B_{nk}^*, \quad B_{hk} \le B_{hk}^*, \quad L_k \le L_k^*, \quad I_0 \le I_0^*, \tag{22}$$

Table 2: Parameter values used.

Symbol	Value	Symbol	Value
N_c	20, 40, or 60	$1/\mu_{h2}$	18/60 min
C_G	3	$1/\mu_{h3}$	18/60 min
r_1	1	$t_1 = t_2 = t_3$	7 dB
r_2	2	$1/\mu_{c1}$	1 min
r_3	2	$1/\mu_{c2}$	2 min
M_1	6	$1/\mu_{c3}$	3 min
M_2	3	$\sigma_1 = \sigma_2 = \sigma_3$	2.5 dB
M_3	2	$(W/N_c)/R_1$	48, 24, or 16
α_1	1/0.650	$R = R_1$	96 kbps
α_2	0.2	R_2	192 kbps
α_3	0.9	R_3	192 kbps
β_1	1/0.352	f	0.576
β_2	0.1	$\eta = N_0/I_0^*$	0.1
β_3	0.1	$B_{n1}^* = B_{n2}^* = B_{n3}^*$	0.1
θ_{n1}	$\theta_{n2} = \theta_{n3}$	$B_{h1}^* = B_{h2}^* = B_{h3}^*$	0.1
$1/\mu_{h1}$	18/60 min	$L_1^* = L_2^* = L_3^*$	5×10^{-5}

where the superscript $*$ denotes the threshold of the corresponding parameter. Numerical results for the maximum system utilization are obtained in Section 6.3 by iteratively increasing the load until the target constraints are met.

6. NUMERICAL RESULTS

In this section we present results to examine the connection- and packet-level performance for the CS scheme with guard capacity, as well as the performance gain in system utilization through joint-layers GoS/QoS coupling. The analytical results have been obtained by means of the foregoing analysis from Section 5, while the simulation results have been obtained from a simulation program coded in C for the connection level and ran with a simulation kernel. We consider three traffic classes ($K = 3$).

The parameter values used in the numerical example presented in this section are tabulated in Table 2.

6.1. Connection-level blocking probabilities and system utilization

The connection-level analytical and simulation results of new and handoff connection blocking probabilities as a function of the new connection arrival rate are shown in Figures 3 and 4, respectively.

For illustration purpose, a nominal capacity of $\mathcal{N} = 24$ and $N_c = 20$ are chosen. Clearly, the larger the load, the larger the blocking probabilities. Figure 5 shows the connection-level analytical and simulation results of system utilization. The larger the load, the higher the system utilization.

6.2. Packet-level packet loss probabilities

Packet loss rates are presented in Figure 6. Intuitively, the larger the load, the larger the packet loss probabilities.

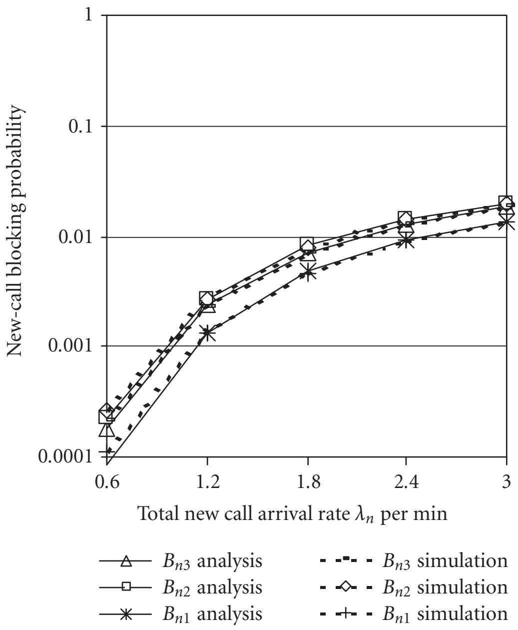

Figure 3: New connection blocking probabilities, where $C_G = 3$, $\mathcal{N} = 24$, and $N_c = 20$.

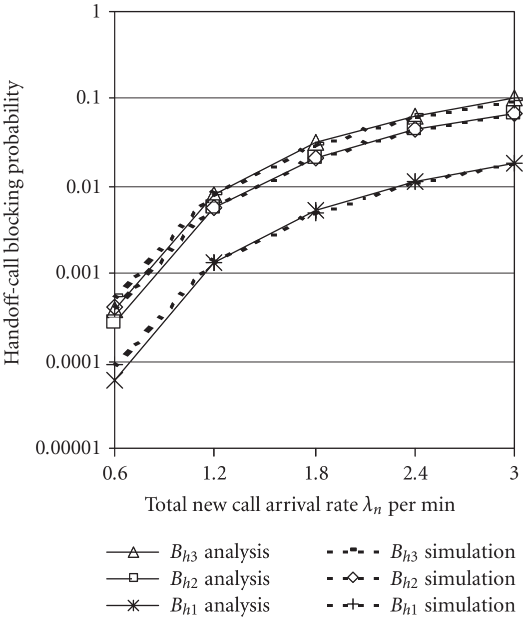

Figure 4: Handoff connection blocking probabilities, where $C_G = 3$, $\mathcal{N} = 24$, and $N_c = 20$.

6.3. Coupling of the connection-level, packet-level, and link-layer GoS/QoS

Figure 7 shows the effect of the gain in system utilization through joint connection-level, packet-level, and link-layer GoS/QoS coupling for $N_c = 20$. The gain in system utilization is the difference between the solid-line curve with coupling and its corresponding dotted-line curve without

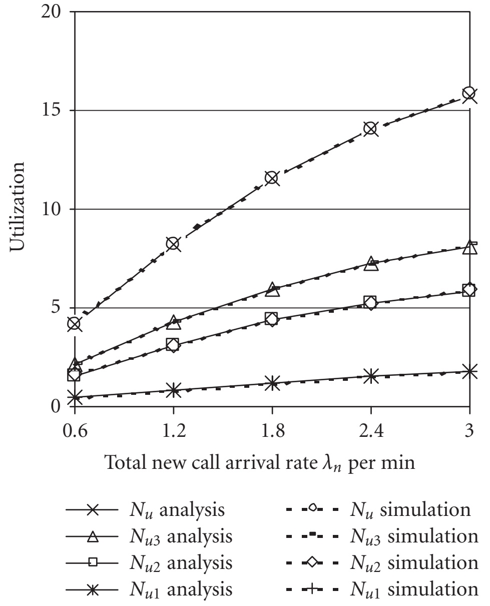

FIGURE 5: System utilization, where $C_G = 3$, $\mathcal{N} = 24$, and $N_c = 20$.

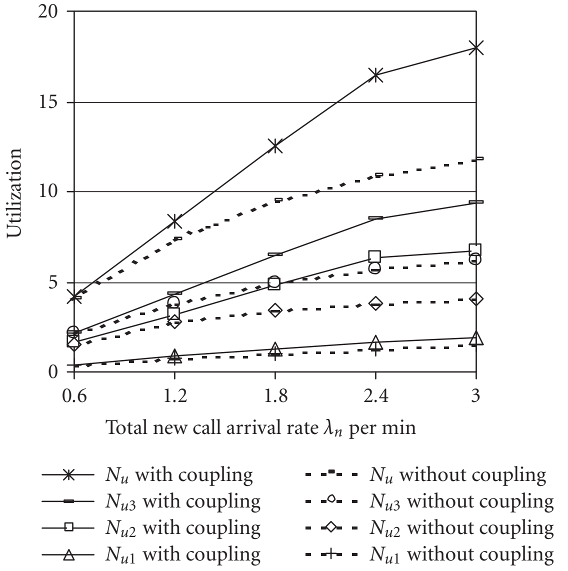

FIGURE 7: System utilization with and without joint connection/packet-level and link-layer GoS/QoS coupling for $N_c = 20$ and $C_G = 3$.

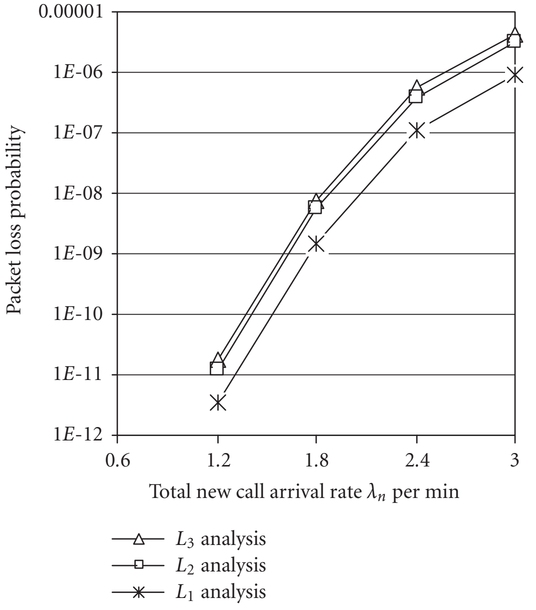

FIGURE 6: Packet loss probabilities, where $C_G = 3$, $\mathcal{N} = 24$, and $N_c = 20$.

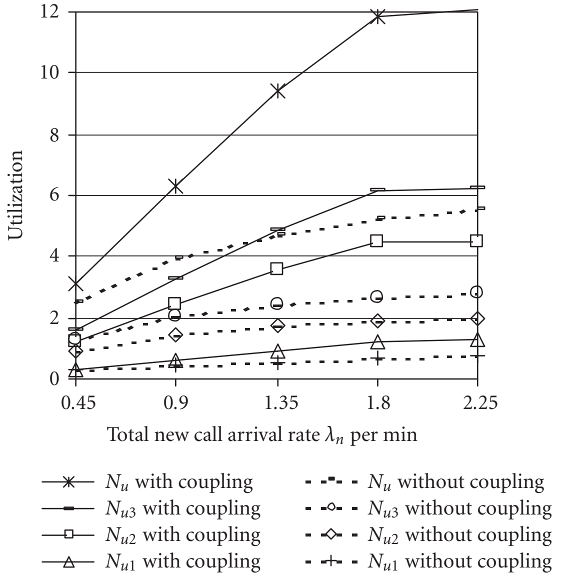

FIGURE 8: System utilization with and without joint connection/packet-level and link-layer GoS/QoS coupling for $N_c = 40$ and $C_G = 3$.

coupling. Without coupling, the nominal capacity is $\mathcal{N} = 17$, from (20). The total nominal capacity $\mathcal{N}$ is increased until the new or handoff connections' blocking probabilities, B_{nk} or B_{hk}, or the packet loss probabilities, L_k, violate any of their respective thresholds.

The point, just before this violation occurs, corresponds to the maximum system utilization N_u and nominal capacity $\mathcal{N}$. With coupling, the nominal capacity $\mathcal{N} = \{> 38, > 38, > 38, > 38, 29\}$ for $\lambda_n = \{0.6, 1.2, 1.8, 2.4, 3.0\}$ per minute. We note that at $\mathcal{N} = 38$, the packet loss probabilities at $\lambda_n = \{0.6, 1.2, 1.8, 2.4\}$ are still very low (in the order of 10^{-11} to 10^{-5}) compared to the constraints of 5×10^{-5}. However, their corresponding system utilization values are already at their maximum values. Thus we can assume these values for $\lambda_n = \{0.6, 1.2, 1.8, 2.4\}$ per minute. At low load, where $\lambda_n = 0.6$ per minute, there is a very small gain in system utilization as the blocking probabilities and packet loss probabilities are low, and they are not curbed by their respective

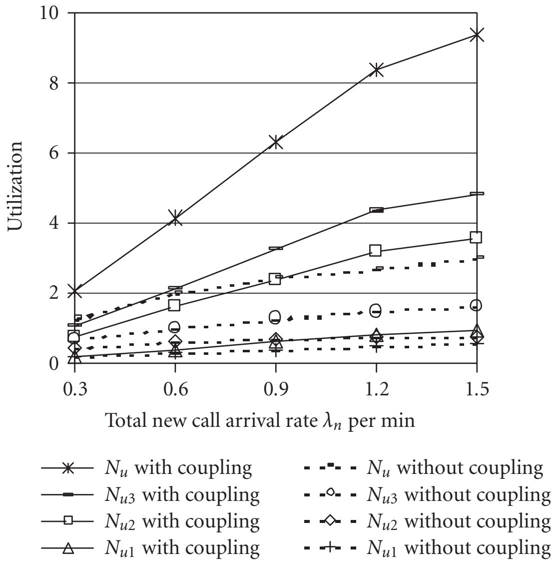

Figure 9: System utilization with and without joint connection/packet-level and link-layer GoS/QoS coupling for $N_c = 60$ and $C_G = 3$.

GoS/QoS constraints in (21). At slightly above mid load, where $\lambda_n = 2.4$ per minute, the gain in system utilization is the largest. At high load, where $\lambda_n = 3.0$ per minute, there is still some gain in system utilization. Beyond that, the system utilization is being curbed by the packet loss probabilities in this numerical example. This means that the system is approaching congestion. Overall, there is a *significant* gain in system utilization.

Figures 8 and 9 show the effect of the gain in system utilization through joint connection-level, packet-level, and link-layer GoS/QoS coupling for $N_c = 40$ and $N_c = 60$, respectively. Without coupling, the nominal capacity is $\mathcal{N} = 9$ and $\mathcal{N} = 17$, respectively, from (20). With coupling, the nominal capacity $\mathcal{N} = \{> 38, > 38, > 38, 26, 20\}$ for $\lambda_n = \{0.45, 0.9, 1.35, 1.8, 2.25\}$ per minute and $\mathcal{N} = \{> 38, > 38, > 38, > 38, 20\}$ for $\lambda_n = \{0.3, 0.6, 0.9, 1.2, 1.5\}$ per minute, respectively. Although the absolute system utilization is larger for a smaller number of subcarriers N_c than those for larger numbers of subcarriers, the gain in system utilization is larger for a larger number of subcarriers than those for small numbers of subcarriers as seen from Figures 7, 8, and 9. The reason for this is that the nominal capacity $\mathcal{N} = 6$ for $N_c = 60$, $\mathcal{N} = 9$ for $N_c = 40$, and $\mathcal{N} = 17$ for $N_c = 20$, respectively. Thus the system utilization for $\mathcal{N} = 17$ is higher than that for $\mathcal{N} = 9$, and that for $\mathcal{N} = 9$ is higher than that for $\mathcal{N} = 6$ due to the increase loading effect of $\mathcal{N}$ as it increases.

7. CONCLUDING REMARKS

An approximate analytical formulation of the resource allocation problem for handling VBR multiclass services in a novel round-robin carrier-hopping multirate MC-DS-CDMA cellular system has been presented in this paper. A complete sharing scheme is used for the resource sharing policy. The analytical model is solved using a K-dimensional Markov chain for the CS scheme. In the formulation, all GoS/QoS requirements are satisfied across the layers simultaneously. Numerical results illustrate that significant gain in system utilization can be achieved through the coupling of the connection/packet-levels and the link-layer parameters. This gain in utilization can translate to possibly more revenue for network providers and/or lower charges for mobile users.

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