Resource Allocation for Video Services in Multirate DS-CDMA Cellular Networks with QoS Constraints

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Abstract - An approximate analytical formulation of the resource allocation problem for handling video services with scene changes in a cellular multirate direct sequence code division multiple access (DS-CDMA) system is presented. The video traffic accounts for slow and fast motions. The novelty in this paper is that all grade of service (GoS) or quality of service (QoS) requirements at the connection level, packet level and link layer are satisfied simultaneously, 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 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. The CS model is solved using a K-dimensional Markov chain. Numerical results illustrate that significant gain in system utilization is achieved through the joint coupling of connection/packet levels and link layer.

1. Introduction

Resource allocation for connection admission at the connection-level typically has new connection and handoff connection blocking probabilities and forced termination probability of handoff connections as grade of service (GoS) measures. These GoS measures, associated with connection admission, are collectively defined as connection level metrics. When traffic flows are admitted into the network proper, quality of service (QoS) is measured in terms of packet loss rate and/or packet delay. These QoS metrics are associated with packet transmission in the system, and are collectively defined as packet level metrics. In this case, scheduling and statistical multiplexing gains play a crucial role in determining the amount of traffic that can be admitted into the network proper while still satisfies the packet level QoS. Satisfying GoS constraints at the connection level alone may limit the size of the traffic load admitted, even though the packet level may still be able to sustain a larger load. There is thus reason to believe that system utilization can be enhanced by making use of both the connection level and packet level properties.

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. They found that a significant improvement in system utilization resulted when the deployment of system resources was subject to simultaneous satisfaction of both packet level QoS and connection level GoS constraints. However, they considered only one traffic class.

For third generation cellular systems and beyond, many types of connections are anticipated, not just voice and data traffic. The connections could be voice, video, data, multimedia, web browsing, etc., which would result in multiclass traffic. In [2], Wong et al. considered a complete sharing scheme with K classes in their numerical results. They found improvement in system utilization with joint coupling of connection/packet levels. In this paper, this idea of joint coupling of connection/packet levels is extended to include the link layer in order to maximize system utilization. When packets are transmitted in a cellular system, the success of the transmissions of these packets depends on whether there is any outage in the system which is influenced by the total interference in the system. The outage QoS metric is associated with the state of the channel in the system and we define it as the link layer. The novelty in this paper is that all GoS/QoS requirements at the connection level, packet level and link layer are satisfied simultaneously, instead of being satisfied at the connection level, packet level or at the link layer only. The packet level QoS (packet loss) is expressed as a function of the link layer QoS (outage probability) while the link layer QoS (outage probability) is dependent on the call level parameter (number of active users) and the packet level parameter (connection multi-rate state). Thus the GoS/QoSs in the different layers are intertwined across the layers. Furthermore, the distribution of the number of active class k connections is explicitly obtained based on the complete sharing (CS) resource allocation scheme at the connection level and not simply assumed to be Poisson distributed as in [3].

In numerous performance analyses of the system outage probability [4-6], the traffic source has often been assumed to be an on/off process which enables simple closed-form solutions in the performance analyses. However, such an assumption is valid only for voice or data traffic but not for video or other traffic which can be modeled as a multi-rate traffic [7-8]. In Sen’s video model [7], each source is modeled by a two-dimensional Markov chain (MC). Sen’s model considers a combination of low- and high-bit-rates. The low-bit-rates account for scenes with slow motion while...
the high-bit-rates account for scenes with fast motion. Since
this video traffic model is more complex than a simple on/off
traffic model, closed-form solution is more difficult, though
not impossible. Maglaris’ video model [8] considers scenes
with only low-bit-rates that can be modeled by a one-
dimensional MC and is a special case of Sen’s model.

Maximization of the system utilization by jointly
satisfying the GoS/QoS constraints at the connection level,
packet level and link layer for a multi-rate DS-CDMA
system has been formulated and assessed in [9]. The
analytical formulation in [9] is based on static sources. But
motion video also has scene changes. The current work
generalizes the analytical model in [9] to account for scene
changes.

In this paper, the performance of the vertical coupling in
the uplink of a multirate DS-CDMA system with Sen’s
video traffic having scene changes is derived. We generalize
the analytical results in [9] for low-bit-rate multiclass
services, modeled by a one-dimensional MC, to low- and
high-bit-rate multiclass video services, modeled by a two-
dimensional MC. Each user uses a combination of low- and
high-bit-rate spreading codes.

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
number of 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

- $C$: total physical capacity in a cell
- $K$: total number of traffic classes
- $r_{uk}$: number of basic channels (units) required by each class $k$’s low-bit-rate spreading code
- $r_{hk}$: number of basic channels (units) required by each class $k$’s high-bit-rate spreading code
- $M_k$: maximum number of active low-bit-rate spreading codes used by each class $k$ connection
- $N > C$: total nominal capacity in a cell (capitalizing on statistical multiplexing gain)

The dynamics of a radio cell is 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 $N$, $C_G$ and $C_i$ denote respectively the total nominal
capacity, 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 $N - C_i \geq C_G$, where $(N-C)$ is the free capacity left after admitting a new
   or handoff connection.
2. Admit only handoff connections if $0 \leq N - C_i < C_G$, where $(N-C)$ is the free capacity left after admitting a handoff
   connection.

Deployment of the guard capacity policy has the following
ramifications:

- A handoff connection is accepted as long as there is
  enough capacity available.
- 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
quality which is determined by the signal-to-interference
ratio (SIR) specification, corresponding to the target bit error
rate (BER) at the link layer. This is the reason that we refer
to $N$ 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, mean delay and delay jitter (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, $P_{outage,k}$, at
the link layer. The goal is to maximize system utilization or
nominal capacity under these GoS/QoS requirements. The
connection level, packet level and link layer parameters used
throughout the paper are listed below.

**Connection level parameters**

- $B_{nk}$: new connection blocking probability for class $k$
- $B_{hk}$: handoff connection blocking probability for class $k$
- $B_n = \sum_{k=1}^{K} B_{nk}$: total new connection blocking probability
- $B_h = \sum_{k=1}^{K} B_{hk}$: total handoff connection blocking probability
- $B = B_n + B_h$: total connection blocking probability

**Packet level parameters**

- $\lambda_n$: arrival rate of class $k$ new connections
- $\lambda_{hk}$: arrival rate of class $k$ handoff connections
- $\lambda_n = \sum_{k=1}^{K} \lambda_{nk}$: arrival rate of class $k$ new connections
- $\lambda_{hk} = \sum_{k=1}^{K} \lambda_{hk}$: arrival rate of class $k$ handoff connections
- $\lambda_k = \lambda_{nk} + \lambda_{hk}$: arrival rate of class $k$ connections
- $\lambda = \sum_{k=1}^{K} \lambda_k$: total connection arrival rate

$\mu_{ck}^{-1}$: mean connection holding time or lifetime of a class $k$ connection
\( \mu^{-1} \): mean dwell time (interhandoff time) of a class \( k \) connection
\( \mu = \mu_{ck} + \mu_{bk} \): mean equivalent rate of a class \( k \) connection
Packet level parameters
\( \alpha_k \): increase rate of a two-state mini-source for a class \( k \) connection
\( \beta_k \): decrease rate of a two-state mini-source for a class \( k \) connection
\( \lambda_k \): increase rate of high-bit-rate fluctuations for a class \( k \) connection
\( \mu_k \): decrease rate of high-bit-rate fluctuations for a class \( k \) connection
\( L_k \): packet loss probability for class \( k \) connection
\( L = \sum_{k=1}^{K} L_k \): total packet loss probability

Link layer parameter
\( P_{\text{outage,k}} \): outage probability for class \( k \) connection

4. Analytical Model
4.1. Connection Level

Consider a \( K \)-class CS model. The guard capacity, \( C_G \), are 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 \([10]\). 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) \([10]\) and model the channel occupancy as an \( K \)-dimensional Markov chain with the connection level parameters in Section 3. This Markov chain can be modeled and solved using the techniques in \([11]\). The connection level GoSs are dependent on the packet level GoS. Thus we need to understand the packet level characteristics before solving for the connection level GoSs. Let us assume that a class \( k \) connection, after being admitted into the system, behaves according to Sen’s model \([7]\). From Sen’s model \([7]\), a VBR video source can be modeled by a 2-dimensional continuous-time MC with finite states as shown in Fig. 1. Each state \((x,m)\) represents the combined discrete level of low- and high-bit-rates that are generated by a single source. The combined data rate of each source is \( mR_k \) plus \( xR_{k,h} \), where \( R_{k,h} \) is the low-bit-rate for user \( k \) using one low-bit-rate spreading code and \( R_{k,h} \) is the high-bit-rate for user \( k \) using one high-bit-rate spreading code. That is, we assume that each level of low- or high-bit rates uses one low- or high-bit-rate spreading code for a class \( k \) user. Each low-bit-rate level is modeled by a two-state mini-source with an increase rate of \( \alpha_k \) and a decrease rate of \( \beta_k \). Thus the 2-dimensional continuous-time MC for a single video source at state \((x,m)\) has an increase rate of \( (M_k - m)\alpha_k \) and a decrease rate of \( m\beta_k \) for low-bit-rate fluctuations, where \( M_k \) is the highest level in the low-bit-rate states, and this is also the maximum number of active spreading codes used by a class \( k \) user for low-bit-rate fluctuations.

Each high-bit-rate fluctuation is modeled by a two-state MC with an increase rate of \( \lambda_k \) and a decrease rate of \( \mu_k \). There are only two states in the high-bit-rate fluctuation. \( x \in \{0,1\} \) represents the high-bit-rate state that the video source is in. State 0 (\( x=0 \)) means that there is no high-bit-rate fluctuations but only low-bit-rate fluctuations, while state 1 (\( x=1 \)) means that there are both low- and high-bit-rate fluctuations. If the high-bit-rate fluctuation has only one state (state 0), then it reduces to Maglaris’ model. Furthermore, if \( M_k = 1 \), the source is an on/off source. The steady-state probability of being in state \( m \), denoted by \( P_m \), is given by a Binomial distribution with parameters \((M_k, \beta_k, \mu_k)\) where \( m=0,1,\ldots,M_k \) and \( p_m=\alpha_k/(\alpha_k+\beta_k) \), while the steady-state probability of being in state \( x \), denoted by \( Q_x \), obeys a Bernoulli distribution with parameters \((q_{x,0})\) where \( x=0,1 \) and \( q_x=\lambda_k/(\lambda_k+\mu_k) \).

Analytical techniques such as those in \([11]\) can be used to solve for the connection level GoSs by blockin probabilities and system utilization. To this end let \( \mathbf{n}=(n_1,n_2,\ldots,n_K) \) denote the state of the system with the number of users \( n_k \) in each of the \( K \) classes, \( r_k=(r_{k,1},r_{k,2},\ldots,r_{k,k}) \) denote the number of basic channels \( r_k \) required for each class \( k \) connection’s high-bit-rate spreading code, \( r_{k,h}=(r_{k,h1},r_{k,h2},\ldots,r_{k,hk}) \) denote the number of basic channels \( r_{k,h} \) required for each class \( k \) connection’s high-bit-rate spreading code, \( \mathbf{m}=(m_1,m_2,\ldots,m_K) \) denote the mean number of active low-bit-rate spreading codes used by each class \( k \) connection, and \( \mathbf{q}=(q_1,q_2,\ldots,q_K) \) denote the mean number of active high-bit-rate spreading codes used by each class \( k \) connection, where \( m_k=M_k\alpha_k/(\alpha_k+\beta_k) \) and \( q_k=\lambda_k/(\lambda_k+\mu_k) \). Let \( \Delta_0(\mathbf{n}) \) denote the arrival rate and \( \mu(\mathbf{n}) \) the departure rate in the system. With \( N \) denoting the total nominal capacity, the state space of the system, denoted by \( S \), is given by \( S=\{\mathbf{n}=(\mathbf{m},\mathbf{r}_{k}\mid q_{k}),0 \leq \mathbf{n} \leq N\} \).

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 \( f=(f_1,\ldots,f_k) \) for new and handoff connections,
Let $\theta_{nk}$ denote the probability that the next arrival is a new class $k$ connection. Then

$$
\theta_{nk} = \lambda_{nk} \sum_{k=1}^{K} \lambda_{k}.
$$

(6)

Similarly, if $\theta_{hk}$ denotes the probability that the next arrival is a class $k$ handoff connection, we have

$$
\theta_{hk} = \lambda_{hk} \sum_{k=1}^{K} \lambda_{k}.
$$

(7)

and if $\theta_{h}$ denotes the probability that the next arrival is a class $k$ connection, we have

$$
\theta_{h} = \lambda_{h} \sum_{k=1}^{K} \lambda_{k}.
$$

(8)

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 $\sum_{k=1}^{K} \lambda_{k} r_{hk}$.

Therefore the blocking probability for a new class $k$ connection considering all classes is given by

$$
B_{hk} = \sum_{n=0}^{N} \cdots \sum_{n=0}^{N} P(n_1, n_2, ..., n_K) \theta_{hk},
$$

(9)

where

$$
N_{k} = \left( N - \sum_{i=1}^{k-1} n_{i} (\sum_{j=0}^{i} \lambda_{j} r_{ij} + q_{i} r_{ij}) \right) < \sum_{i=1}^{K} \lambda_{i} r_{ih} + q_{l} r_{ih}.
$$

The total system utilization, defined as the number of basic rate users that can be supported, for class $k$ connections is given by

$$
N_{uk} = \sum_{n=0}^{N} \cdots \sum_{n=0}^{N} P(n_1, n_2, ..., n_K) \theta_{hk},
$$

(10)

and

$$
B_{uk} = \sum_{k=1}^{K} B_{hk}.
$$

(11)

The system utilization is

$$
N_{u} = \sum_{k=1}^{K} N_{uk}.
$$

(12)

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:

$$
\lambda_{hk} = \mu_{hk} \lambda_{hk} / \mu_{hk}.
$$

(13)

where $1/\mu_{hk}$ is the mean dwell time (interhandoff time) of a class $k$ connection, $\lambda_{hk}$ is the arrival rate of class $k$ new connections and $1/\mu_{hk}$ is the mean connection holding time of a class $k$ connection.

To solve for the link layer QoS of outage probability in Section 4.3, the first and second moments, and the variance
of the number of active class \( k \) connections, \( n_k \), are needed. Using the definition of marginal distribution, the pmf of \( n_k \), denoted by \( P(n_k) \), is given by
\[
P(n_k) = \sum_{n_{k-1}=0}^{N_k-1} \sum_{n_{k+1}=0}^{N_k} \cdots \sum_{n_K=0}^{N_K} P(n_1, \ldots, n_{k-1}, n_k, n_{k+1}, \ldots, n_K),
\]
where
\[
n_k = 0,1,\ldots,n_{k,\max}
\]
and
\[
n_{k,\max} = \left\lfloor \frac{N}{\overline{n}_k, q_k + r_{k,R}} \right\rfloor.
\]
Thus the mean, second moment and variance of \( n_k \), denoted by \( \overline{n}_k \), \( \overline{n}_k^2 \) and \( \text{Var}[n_k] \), respectively, are 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
\[
\text{Var}[n_k] = \overline{n}_k^2 - \overline{n}_k^2.
\]
Note that the distribution of the number of active class \( k \) connections, \( n_k \), is explicitly obtained based on the CS resource allocation scheme at the connection level and not simply assumed to be Poisson distributed as in [3].

The connection admission used here at the connection level is based on \( M \) and \( q \) which are 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.

### 4.2. Packet Level

From the Markov chain of the packet level variable bit rate model in Fig. 2, the steady-state probability of being in state \( x \), denoted by \( Q_x \), is given by
\[
Q_x = \frac{1}{q_k} \left( 1 - q_k \right)^x, \quad x = 0,1,2,\ldots
\]
where \( q_k = \lambda_k / (\lambda_+ + \mu_0) \). The steady-state probability of being in state \( m_k \) denoted by \( P_{m_k} \), is given by
\[
P_{m_k} = \left( \frac{M_k}{m_k} \right)^{m_k} \left( 1 - \frac{M_k}{m_k} \right)^{M_k - m_k}, \quad m_k = 0,1,\ldots,M_k,
\]
where \( p_k = a_k / (\alpha_k + \beta_k) \). Being in state \( (x, m_k) \) means that a packet source is generating data at rate \( m_k R_{l,k} + x R_{h,k} \) and \( m_k \) active low-bit-rate and \( x \) active high-bit-rate spreading codes are needed to transmit the data; each low-bit-rate and high-bit-rate spreading codes has a data rate of \( R_{l,k} \) and \( R_{h,k} \), respectively.

To solve for the link layer QoS of outage probability in Section 4.3, the first and second moments, and the variances of the number of active high-bit-rate class \( k \) spreading codes used, \( n_k \), are needed. Their means, second moments and variances are respectively given by
\[
\overline{q}_k = q_k, \quad \overline{x}_k = q_k,
\]
\[
\overline{x}_k^2 = q_k^2,
\]
\[
\overline{y}_k = M_k p_k, \quad \overline{y}_k^2 = M_k p_k (1 - p_k), \quad \text{Var}[x] = q_k (1 - q_k).
\]
\[
\text{Var}[y] = M_k p_k (1 - p_k).
\]

For a stationary admission control policy, the underlying process is Markovian. Let
- \( r_{l,k} = R_{l,k} / R \), 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 low-bit-rate spreading codes.
- \( r_{h,k} = R_{h,k} / R \) be the number of basic channel capacity a class \( k \) connection needs to transmit its packets for its high-bit-rate spreading code.
- \( n_k \) be the number of class \( k \) connections in progress.
- \( l_k \) be the number of active low-bit-rate spreading codes used by \( n_k \) class \( k \) connections.
- \( h_k \) be the number of active high-bit-rate spreading codes used by \( n_k \) class \( k \) connections.

The probability that \( l_k \) active low-bit-rate spreading codes are used given that there are \( n_k \) connections in progress is given by
\[
P(l_k \mid n_k) = \left( n_k M_k / l_k \right)^{l_k} (1 - n_k M_k / l_k)^{M_k - l_k}, \quad l_k = 0,1,\ldots,n_k M_k.
\]

The probability that \( h_k \) active high-bit-rate spreading codes are used given that there are \( n_k \) connections in progress is given by
\[
P(h_k \mid n_k) = \left( n_k h_k / h_k \right)^{h_k} (1 - n_k h_k / h_k)^{h_k - h_k}, \quad h_k = 0,1,\ldots,n_k.
\]

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
\[
L_{k} = \left( \frac{N_1}{N_1} \sum_{n_1=0}^{N_1} \sum_{n_2=0}^{N_2} \cdots \sum_{n_K=0}^{N_K} \frac{P(n_1, n_2, \ldots, n_K)}{\sum_{l_1=0}^{l_1} \cdots \sum_{l_K=0}^{l_K}} \frac{n_1 M_1 n_2 M_2 \cdots n_K M_K}{l_1 \cdots l_K} \right.
\]
\[
\times \sum_{l_1=0}^{n_1} \sum_{h_1=0}^{l_1} \cdots \sum_{h_K=0}^{l_K} \frac{P(h_1 \mid n_1) P(h_2 \mid n_2) \cdots P(h_K \mid n_K)}{l_1 \cdots l_K} \left. \right),
\]
where
\[
L_{sum} = \frac{N_1}{N_1} \sum_{n_1=0}^{N_1} \sum_{n_2=0}^{N_2} \cdots \sum_{n_K=0}^{N_K} \frac{P(n_1, n_2, \ldots, n_K)}{\sum_{l_1=0}^{l_1} \cdots \sum_{l_K=0}^{l_K}} \frac{n_1 M_1 n_2 M_2 \cdots n_K M_K}{l_1 \cdots l_K} \times \sum_{l_1=0}^{n_1} \sum_{h_1=0}^{l_1} \cdots \sum_{h_K=0}^{l_K} \frac{P(h_1 \mid n_1) P(h_2 \mid n_2) \cdots P(h_K \mid n_K)}{l_1 \cdots l_K} \right).
\]
and $P_{\text{outage}}$ is the outage probability for class $k$ connections which is defined in equation (41). The total packet loss probability is given by

$$L = \sum_{k=1}^{K} L_k.$$

(34)

### 4.3. Link Layer

To solve for the link layer QoS of outage probability in this section, the first and second moments, and the variance of the required energy-to-interference density ratio ($E_o/I_o$) for each class $k$ connection are required. Let $q_k$ denote the required energy-to-interference density ratio ($E_o/I_o$) for each class $k$ connection under some propagation conditions. Assuming that the class $k$ signal emerging from the propagation channel is lognormal-distributed with a normal mean of $t_k$ and a normal variance of $\sigma_k^2$. The mean and second moment of $q_k$ are respectively given by

$$\bar{q}_k = \exp(2/\beta \sigma_k^2),$$

and

$$\bar{q}_k^2 = \exp(2/\beta \sigma_k^2 + 2\beta t_k),$$

where $\beta=\ln(10)$. Its variance is thus

$$\text{Var}(\bar{q}_k) = \exp(2(\beta \sigma_k^2) + 2\beta t_k) - \exp(2(\beta \sigma_k^2 + 2\beta t_k)).$$

(37)

We consider the uplink capacity and define the outage to occur when the total influence of the users, both intra-cell and inter-cell, introduces an amount of interference density $I_o$ so great that it exceeds the background noise level $N_0$ by an amount $I_o/N_0=1/\eta$. From [3], the conditions for no outage for class $i$ users is as follows:

$$\sum_{j=1}^{n_i} q_{0j} \left( \frac{m_{0ij} R_{j,i}}{W} + q_{0j} R_{h,j} / W \right) + \sum_{k=1, k \neq i}^{K} \sum_{j=1}^{n_k} q_{kj} \left( m_{kij} R_{j,i} / W + q_{kj} R_{h,k} / W \right) \leq (1 - \eta),$$

where the first term on the left hand side of inequality (38) is the intra-cell interference from its own class, the second term is the inter-cell interference from other classes, the third term is the inter-cell interference from all classes, $R_{h,i}$ is the data rate of class $i$'s low-bit-rate spreading code, $R_{h,k}$ is the spread-spectrum bandwidth and $N_{BG}$ is the number of cells contributing to inter-cell interference. Dividing inequality (38) by $R_{h,i}/W$, the outage condition becomes

$$Z_i = \sum_{j=1}^{n_i} q_{0j} \left( \frac{m_{0ij} R_{j,i}}{W} + q_{0j} R_{h,j} / W \right) + \sum_{k=1, k \neq i}^{K} \sum_{j=1}^{n_k} q_{kj} \left( m_{kij} R_{j,i} / W + q_{kj} R_{h,k} / W \right) \leq \frac{W}{R_{j,i}} (1 - \eta),$$

(39)

and, on the basis that connections within the same class have identical characteristics, we replace the $j$ summations by $n_i$ and $n_k$ to yield

$$Z_i = n_i q_{0i} \left( m_{0i} + q_{0i} R_{h,i} / R_{j,i} \right) + \sum_{k=1, k \neq i}^{K} n_k q_{ki} \left( m_{kij} R_{j,i} / R_{j,i} + q_{ki} R_{h,k} / R_{j,i} \right) \leq \frac{W}{R_{j,i}} (1 - \eta).$$

(40)

Thus, the class $i$ outage probability, $P_{\text{outage}}$, for DS-CDMA becomes

$$P_{\text{outage}} = \Pr [Z_i > W/R_{j,i} (1 - \eta)].$$

(41)

Invoking the central limit approximation for $Z_{t_0}$ and computing its mean and variance, the class $i$ outage probability can be written as

$$P_{\text{outage}} = \Pr \left[ \frac{\bar{Z}_i - \eta W}{\sqrt{\text{Var}(Z_i)}} > 1 \right].$$

(42)

where

$$E[Z_i] = \left[ \eta \left( m_{0i} + q_{0i} R_{h,i} / R_{j,i} \right) \exp(\beta \sigma_i^2 / 2 + \beta t_i) \right] + \sum_{k=1}^{K} \sum_{k \neq i}^{K} q_{ki} \left( m_{kij} R_{j,i} / R_{j,i} + q_{ki} R_{h,k} / R_{j,i} \right) \text{exp}(\beta \sigma_k^2 / 2 + \beta t_k)$$

(43)

and

$$\text{Var}(Z_i) = \eta \left( m_{0i} + q_{0i} R_{h,i} / R_{j,i} \right) \text{exp}(\beta \sigma_i^2 / 2 + \beta t_i) \left[ 1 - \left( \exp(\beta \sigma_i^2 / 2 + \beta t_i) \right) \right] + \sum_{k=1}^{K} \sum_{k \neq i}^{K} q_{ki} \left( m_{kij} R_{j,i} / R_{j,i} + q_{ki} R_{h,k} / R_{j,i} \right) \text{exp}(\beta \sigma_k^2 / 2 + \beta t_k) \times (1 + f),$$

(44)

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-t^2/2} dt,$$

and $f$ is the other cell to own cell relative interference factor. Equation (44) is obtained by making use of the result of substituting equations (18), (19), (20), (23), (24), (25), (26), (27), (28), (35), (36) and (37) into the following equations with some algebraic manipulations:

$$\text{Var}(n_i q_{0i} e_i) = E[n_i^2 \left[ \text{Var}(q_{0i}) \right] \text{E}[e_i^2] + \text{Var}(e_i) \left[ \text{E}(q_{0i}) \right]^2 \right]$$

+ $\text{Var}(n_i) \left[ \text{E}(q_{0i}) \right]^2 \text{E}(e_i^2)$

(45)

and

$$\text{Var}(n_i m_{ij} e_i) = E[n_i^2 \left[ \text{Var}(m_{ij}) \right] \text{E}[e_i^2] + \text{Var}(e_i) \left[ \text{E}(m_{ij}) \right]^2 \right]$$

+ $\text{Var}(n_i) \left[ \text{E}(m_{ij}) \right]^2 \text{E}(e_i^2)$

(46)

Note that equations (46) and (47) represent the variance of a generic term in equation (40). Clearly, from equations (42), (43), and (44), the link layer class $i$ outage probability is a function of not just the link layer characteristics ($s_n$, $t_i$) of the required energy-to-interference density ratios, but also a function of the connection level characteristics ($n_i$) of the number of users of different classes as well as a function of
the packet level characteristics \((M_k, p_k, q_k)\) of the video sources.

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 \(N\) without coupling is given by

\[
N = \max \left\{ n_{1, \text{limit}, 1} \left( \overline{m}_1 + \delta_1 \right), n_{2, \text{limit}, 1} \left( \overline{m}_2 + \delta_2 \right), \ldots, n_{K, \text{limit}, K} \left( \overline{m}_K + \delta_K \right) \right\},
\]

where

\[
n_{k, \text{limit}, i} = \min \left\{ n_{k, \text{limit}, i}, n_{k, \text{limit}, h} \right\},
\]

\[
n_{k, \text{limit}, h} = \frac{W}{R_{i,k}} \frac{1 - \eta}{\delta_k} + 1, \tag{49}
\]

and \(M_k\) is the maximum number of active low-bit-rate spreading codes for a class \(k\) connection.

4.4. 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 \(N\). The maximization can be achieved by solving the following coupling problem:

\[
\max \{ N_u \} \text{ or } \max \{ N \} \tag{52}
\]

subject to the constraints

\[
B_{nk} \leq B_{nk}^*, \quad B_{hk} \leq B_{hk}^*, \quad L_k \leq L_k^* \quad \text{and} \quad I_0 \leq I_0^*,
\]

where the superscript * denotes the threshold of the corresponding parameter. Numerical results for the maximum system utilization are obtained in Subsection 5.1 by iteratively increasing the load until the target constraints are met.

5. 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 numerical results have been obtained by means of the foregoing analysis from Section 4. We consider three traffic classes (\(K=3\)).

Because of space limitation, we only present an illustrative example. The parameter values used in the numerical example are tabulated in Table 1.

### Table 1. Parameter Values Used

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CG)</td>
<td>2</td>
<td>(1 / \mu h_3)</td>
<td>18/60 minute</td>
</tr>
<tr>
<td>(\rho_1)</td>
<td>1</td>
<td>(q_1 = q_2 = q_3)</td>
<td>7 dB</td>
</tr>
<tr>
<td>(\rho_{2,1} = \rho_{2,2} = \rho_{2,3})</td>
<td>2</td>
<td>(1 / \mu_{h_2})</td>
<td>2 minutes</td>
</tr>
<tr>
<td>(M_1)</td>
<td>1</td>
<td>(1 / \mu_{h_3})</td>
<td>3 minutes</td>
</tr>
<tr>
<td>(M_2 = M_3)</td>
<td>2</td>
<td>(\sigma_1 = \sigma_2 = \sigma_3)</td>
<td>2.5 dB</td>
</tr>
<tr>
<td>(\sigma_1)</td>
<td>0.650</td>
<td>(W / R_{i,1})</td>
<td>32</td>
</tr>
<tr>
<td>(\sigma_2)</td>
<td>0.1</td>
<td>(R = R_{i,1})</td>
<td>9.6 kbps</td>
</tr>
<tr>
<td>(\alpha_3)</td>
<td>0.2</td>
<td>(R_{c,1} = R_{c,3} = R_{c,1}^*)</td>
<td>19.2 kbps</td>
</tr>
<tr>
<td>(\beta_1)</td>
<td>0.150</td>
<td>(R_{h,2} = R_{h,3})</td>
<td>38.4 kbps</td>
</tr>
<tr>
<td>(\beta_2)</td>
<td>0.1</td>
<td>(f)</td>
<td>0.576</td>
</tr>
<tr>
<td>(\beta_3)</td>
<td>0.2</td>
<td>(\eta = N_0/10^*)</td>
<td>0.1</td>
</tr>
<tr>
<td>(q_1 = q_2 = q_3)</td>
<td>0.375</td>
<td>(R_{h,1} = R_{h,2} = R_{h,3})</td>
<td>0.1</td>
</tr>
<tr>
<td>(\beta_{h1})</td>
<td>(\theta_{h2} = \theta_{h3})</td>
<td>(R_{h,1} = R_{h,2} = R_{h,3})</td>
<td>0.1</td>
</tr>
<tr>
<td>(1 / \mu_{h_1})</td>
<td>18/60 minute</td>
<td>(I_1^* = I_2^* = I_3^*)</td>
<td>(1 \times 10^{-2})</td>
</tr>
<tr>
<td>(1 / \mu_{h_2})</td>
<td>18/60 minute</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. System utilization with and without joint connection/packet levels and link layer GoS/QoS coupling

The total nominal capacity, \(N\), 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, \(N\). With coupling, the nominal capacity \(N_u\) increases significantly compared to \(N\). However, their corresponding system utilization values are already at their maximum values. Thus we can assume these values for \(\lambda_u = \{0.075,0.15,0.225\}\) per minute. At low load, where \(\lambda_u = 0.075\) per minute, there is some gain in system utilization as the blocking probabilities and packet loss probabilities are low, and they are not curbed by their respective GoS/QoS constraints in equation (52). At slightly above mid load, where \(\lambda_u = 0.3\) per minute,
the gain in system utilization is the largest. At high load, where $\lambda_n = 0.375$ per minute, the gain in system utilization is actually small because this gain in system utilization is curbed by the packet loss probabilities QoS constraints in this numerical example. This means that the system is congested. Overall, there is a significant gain in system utilization. This translates to possibly more revenue for the network providers and/or lower charges for the mobile users.

6. Concluding Remarks

An approximate analytical formulation of the resource allocation problem for handling video services with scene changes in a multirate 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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References