Fair Resource Allocation with Guaranteed Statistical QoS for Multimedia Traffic in Wideband CDMA Cellular Network

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Abstract—A dynamic fair resource allocation scheme is proposed to efficiently support real-time and non-real-time multimedia traffic with guaranteed statistical quality of service (QoS) in the uplink of a wideband code-division multiple access (CDMA) cellular network. The scheme uses the generalized processor sharing (GPS) fair service discipline to allocate uplink channel resources, taking into account the characteristics of channel fading and intercell interference. In specific, the resource allocated to each traffic flow is proportional to an assigned weighting factor. For real-time traffic, the assigned weighting factor is a constant in order to guarantee the traffic statistical delay bound requirement; for non-real-time traffic, the assigned weighting factor can be adjusted dynamically according to fading channel states and the traffic statistical fairness bound requirement. Compared with the conventional static-weight scheme, the proposed dynamic-weight scheme achieves capacity gain. A flexible trade-off between the GPS fairness and efficient resource utilization can also be achieved. Analysis and simulation results demonstrate that the proposed scheme enhances radio resource utilization and guarantees statistical QoS under different fairness bound requirements.

Index Terms—Resource allocation, generalized processor sharing, W-CDMA cellular network, quality of service, multimedia traffic.

1 Introduction

Future wireless communication networks are expected to support multimedia traffic, such as video, voice, and data, with a variety of quality of service (QoS) requirements and to make efficient use of the radio resources. One promising approach to efficient QoS support is dynamic resource allocation, which takes into account the variation of traffic load and channel conditions [1], [2], [3]. The radio resources should be allocated in a fair manner so that each user can be guaranteed the agreed upon QoS, even though other users may be greedy in demanding bandwidth. How to ensure fairness while efficiently supporting QoS for multimedia traffic in wireless networks is an important problem which has recently attracted more and more attention [4], [5], [6]. The works in [4], [5], [6] extend the existing fair scheduling schemes developed for wireline networks, such as generalized processor sharing (GPS) [7], to time-division multiple access (TDMA)-based and hybrid time-division/code-division multiple access (TD/CDMA)-based wireless networks. These schemes are implemented using a conventional time-scheduling approach, requiring high complexity due to the intensive computation for the virtual-time of each packet [8]. On the other hand, the time-scheduling approach is not fully suited to CDMA-based wireless networks since the radio resources in such networks are mainly related to the spreading bandwidth, transmission power, and channel rates [9]. Fair resource allocation schemes need to be redesigned in order to improve radio resource utilization and achieve fairness with low complexity in such CDMA-based wireless networks.

An important issue in wireless cellular networks is the effect of multipath channel fading on the link capacity. The effect of multipath fading on the uplink capacity of conventional power-controlled CDMA cellular networks has been investigated in [10], [11]. Even with perfect close-loop power control, multipath channel fading may cause a significant reduction in the uplink capacity because the mobile stations (MSs) in deep fading attempt to transmit signals with very high power which causes a substantial increase in intercell interference. The variability of the capacity is also increased due to an enlarged variation of the intercell interference. The reduction and variability of uplink capacity can cause inefficiency of fair resource allocation for QoS support. One approach to improve the efficiency is to apply combined rate and power control, taking into account the channel fading conditions [12]. A rate scheduler, which performs rate control, allocates more bandwidth to the MSs with good channels and less bandwidth to others in bad channel conditions. Such an approach is referred to as opportunistic scheduling [13]. The opportunistic scheduling has the drawbacks of:

1. the lack of short-term fairness (although the long-term asymptotical fairness can be achieved [14]),
2. not supporting the GPS service discipline and, therefore, being difficult to support QoS for multimedia traffic, and
3. implementation complexity for the CDMA uplink.

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In [15], a rate-scheduling approach based on GPS is applied to the CDMA downlinks. Given the limit of the total downlink transmission power, the rate-scheduling scheme dynamically allocates the downlink power and rates according to weights assigned to the users. The user weights are optimized for each scheduling period to guarantee the required minimum channel rates, adapting to the time-varying channel condition, at the cost of high complexity. However, the short-term fairness cannot be guaranteed due to the frequent adjustment of the weights. In [16], a low-complexity code-division GPS (CDGPS) scheme for dynamic fair scheduling is proposed. The scheme makes use of the adaptive feature in the wideband CDMA physical layer to efficiently support QoS for multimedia traffic and uses a fixed weight assignment to guarantee GPS fairness. A low-complexity GPS-based bandwidth scheduling scheme similar to the CDGPS is also proposed in [17], where a multicarrier CDMA system is considered. However, both schemes are designed without considering the effect of multipath fading on link capacity in the cellular network.

In this paper, a dynamic fair resource allocation scheme is proposed to efficiently support both real-time and non-real-time (multimedia) traffic with guaranteed statistical quality of service (QoS) in the uplink of a wideband code-division multiple access (CDMA) cellular network. The scheme uses the generalized processor sharing (GPS) fair service discipline to allocate uplink channel resources, taking into account the characteristics of channel fading and intercell interference. In specific, the resource allocated to each traffic flow is proportional to an assigned weighting factor. For real-time traffic, the assigned weighting factor is a constant in order to guarantee the traffic statistical delay bound requirement (i.e., the probability of exceeding a maximal delay requirement is smaller than a prescribed value); for non-real-time traffic, the assigned weighting factor can be adjusted dynamically according to fading channel states and the traffic statistical fairness bound requirement (i.e., the probability to achieve the GPS fairness is larger than a prescribed value). Analysis and simulation results are given to demonstrate that the proposed fair resource allocation scheme can

1. guarantee statistical QoS delay bound for real-time traffic and a statistical fairness bound for non-real-time traffic,
2. improve the uplink capacity, and
3. achieve efficient radio resource utilization.

The rest of this paper is organized as follows: Section 2 describes the system model. In Section 3, dynamic fair resource allocation schemes for real-time and non-real-time traffic are presented. Section 4 gives an analysis of the capacity gain achieved by the proposed scheme. Section 5 presents simulation results, followed by concluding remarks in Section 6.

2 System, Channel, and Traffic Models

2.1 Rate-Scheduled DS-CDMA System Model

We consider a frequency-division duplex (FDD) wideband DS-CDMA cellular network and focus on the media access control (MAC) protocol for uplink transmission. The physical layer is similar to that of the standard W-CDMA systems [18]. The physical channels, separated by pseudo-noise (PN) codes, comprise a small number of random access channels and a large number of dedicated channels. Each MS is assigned to at least one dedicated data channel. There are also control channels which are used for transmitting system control signals, such as pilot signals and power control commands. It is assumed that the random access channels and control channels consume only a small portion of the uplink capacity, which is negligible compared to the capacity reserved for the dedicated channels bearing multimedia user traffic. The maximum achievable throughput of all dedicated channels is referred to as the uplink capacity. Due to the multiple access interferences (MAI) among uplink channels, the uplink capacity is considered to be interference-limited.

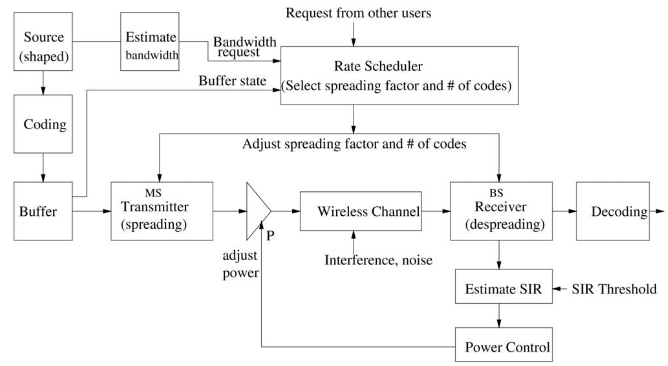


Fig. 1. Rate-scheduled wideband DS-CDMA system.

Fig. 1 illustrates the centralized bandwidth scheduling mechanism to allocate the CDMA system resources [16]. Each MS generates a sequence of packets which enter a buffer after error control coding. The packetized information sequence is then converted to a DS-CDMA signal, power controlled, and transmitted over the wireless channel to the base station (BS). The BS uses a single-user Rake receiver to detect the signal from each MS. The channel rate is dynamically allocated by the rate scheduler at the BS. The spreading factor is adjusted according to the scheduled channel rate. The duration between two consecutive updates of the channel rate is a scheduling period. A signal-to-interference-ratio (SIR) based close-loop fast power control mechanism is in place to achieve a target bit error rate (BER) at the receiver side of each dedicated uplink channel. An SIR threshold corresponding to the target BER and the allocated channel rate is set at the receiver side. When a new channel rate is scheduled, the SIR threshold is adjusted accordingly. The home BS measures the received SIR and compares it with the SIR threshold. When the actual SIR is lower (higher) than the threshold, a feedback control signal is sent to the transmitter to increase (decrease) the transmission power.

A demand-assignment slotted MAC scheme is applied to support the scheduler. Under the MAC scheme, the uplink channels for different users are synchronized at the time-slot level, where the duration of a time-slot, denoted by T, is equal to the scheduling period. This scheme does not require strict bit synchronization among different channels and can be supported in asynchronous DS-CDMA systems.

When an MS has data to transmit, it sends a bandwidth request to the BS through its own dedicated channel or an uplink control channel. Upon receiving the bandwidth requests from all the active MSs, the scheduler allocates the channel rate for the next scheduling period, taking into account user QoS requirements and the available uplink capacity. The resource allocation message is sent back to the MSs before the start of the next scheduling period via a downlink control channel or by piggybacking on the downlink data channel of the MS. Upon receiving a resource allocation message indicating that the rate needs to be changed, the MS immediately adjusts its channel rate and the transmission power accordingly at the beginning of the next scheduling period. The channel rates of different users are changed simultaneously so that all the uplink transmissions can be synchronized.

2.2 Multipath Fading Channel

Let the transmitted power of mobile i be P_{Ti}. The received power P_{ij} at the jth BS is [10], [11]

$$P_{ij} = P_{Ti} r_{ij}^{-\mu} 10^{\xi_{ij}/10} X_{ij}, \tag{1}$$

where r_{ij} is the distance between the ith mobile and the jth BS, μ is the path-loss exponent, ξ_{ij} is a Gaussian random variable with zero mean, and a standard deviation σ, X_{ij} characterizes the multipath fading between MS i and BS j. Let M denote the number of resolvable paths of each multipath fading channel, which is assumed to be independent of the MS and BS. The signals received by the BS from different paths are assumed to be independently faded. The envelopes of the received signals are Rayleigh distributed. After RAKE combining, the total received signal power is the sum of received powers from all the M paths. Under the assumption of equal strength fading paths, X_{ij} has a chi-square probability density function (pdf) with $2M$ degrees of freedom, i.e.,

$$f_X(x) = \frac{M^M}{(M-1)!} x^{M-1} e^{-Mx} U(x), \tag{2}$$

where $U(x)$ is the step function of x and the mean value of X_{ij} is normalized to unity. For a slow multipath fading channel, X_{ij} is approximately constant within each scheduling period. It is shown in [20] that power control can be nearly perfect in compensating for slow channel fading and maintaining the target BER.

2.3 Traffic Model and QoS Requirements

Packetized multimedia traffic flows (such as packet voice, video, and data) are considered with QoS requirements on packet delay and loss rate. In the target cell, there are a total of N active MSs, among which N_v MSs generate real-time traffic and $N_d\ (= N - N_v)$ MSs generate non-real-time traffic. The GPS discipline [7] is applied in resource allocation for both real-time and non-real-time traffic. Let N be the number of packet flows in the cell. The bandwidth requirements of all the flows are characterized by positive real numbers $\phi_1, \phi_2, \ldots, \phi_N$. Let $S_i(t_1, t_2)$ be the amount of services received by flow i in an interval $(t_1, t_2]$. A user that has continuously backlogged traffic during $(t_1, t_2]$ is called a greedy user. GPS fairness is achieved when the following inequality holds for any greedy user i in the interval $(t_1, t_2]$:

$$\frac{S_i(t_1, t_2)}{S_j(t_1, t_2)} \geq \frac{\phi_i}{\phi_j}, j = 1, 2, \ldots, N. \tag{3}$$

For real-time traffic such as voice and video, in order to achieve a required delay bound, each traffic source is shaped by a Leaky-Bucket regulator [21] and is specified by a unique 5-tuple $(\rho_i, R_{m,i}, \sigma_i, D_i, L_i)$, where ρ_i is the token rate, $R_{m,i}$ is a constraint on the peak rate, σ_i is the token buffer size, D_i is the required delay bound, and L_i is the required loss rate. The loss rate L_i reflects both the losses due to transmission errors and the excessive queuing delay. Since a packet lost due to transmission error can be considered as an infinitely delayed packet, the loss rate L_i can be considered equivalent to the probability of delay bound violation. Let $\tau_i(t)$ denote the actual delay of user i traffic arrived at time t. Then, the QoS requirement of a real-time traffic can be stated as a statistical delay bound requirement, i.e.,

$$P\{\tau_i(t) > D_i\} < L_i. \tag{4}$$

In terms of non-real-time traffic, for MS i and MS m which are greedy during (t_1, t_2), define a fairness index F_{im} as

$$F_{im} = \left| \frac{\frac{S_i(t_1,t_2)}{\phi_{d,i}} - \frac{S_m(t_1,t_2)}{\phi_{d,m}}}{S_i(t_1, t_2)/\phi_{d,i}} \right|. \tag{5}$$

The fairness index indicates the difference between the services (normalized by weights) received by the two MSs. When $F_{im} = 0$, GPS fairness is achieved between the two MSs. The larger the F_{im} is, the less fair the scheduling scheme is for the two MSs. A fairness bound, ϕ, is to be guaranteed with probability θ, i.e.,

$$P\{F_{im} > \phi\} < \theta. \tag{6}$$

The amount of service $S_i(t_1, t_2)$ represents either the information bits that user i can transmit or the amount of radio resources that it can use during the interval (t_1, t_2). Here, we consider the resource fairness constraint in the fair scheduling of non-real-time traffic, where $S_i(t_1, t_2)$ represents the radio resources (e.g., power) allocated to MS i.

3 Fair Resource Allocation with Guaranteed Statistical QoS

For fair resource allocation, it is necessary to know the available capacity for allocation. An important feature of CDMA cellular networks is the so-called soft-capacity, i.e., the uplink capacity in terms of the total achievable service rate in each cell may change due to the variation of bandwidth demands and interference. The soft-capacity can cause inefficiency of the conventional fair scheduling schemes for fixed (hard) capacity. In order to address this issue, we first introduce a concept of *nominal capacity* [16], then propose fair resource allocation schemes for real-time and non-real-time multimedia traffic.

3.1 Characterization of the Soft Uplink Capacity

Consider the target cell with a total of N active users in the uplink. Let R_i be the channel rate and P_i the received signal power of MS i in the cell, respectively. The SIR of the MS-i signal can be written as

$$\Gamma_i = \frac{P_i}{\sum_{j \neq i} P_j + P_n + I}, \tag{7}$$

where P_n is the background noise power at the BS, I is the power of intercell interference. Let E_b denote the bit energy of the signal from MS i, I_e the equivalent spectral density of the interference plus background noise for MS i, and W the spread bandwidth of the DS-CDMA system. We have

$$\left(\frac{E_b}{I_e}\right)_i = \frac{W}{R_i}\Gamma_i. \tag{8}$$

To achieve the target BER, a minimum E_b/I_e requirement, $(E_b/I_e)_{r,i}$, should be guaranteed. Let $\gamma_{r,i}$ denote the required minimum SIR for MS i, then $\gamma_{r,i} = (E_b/I_e)_{r,i} R_i/W$.

From (7), if SIR_i can be maintained at the desired level γ_i under a SIR-based fast power control, for any $i = 1, \ldots, N$, the following received power can be derived:

$$P_i^* = \frac{P_n + I}{1 - \sum_{j=1}^{N} \frac{\gamma_{r,j}}{1+\gamma_{r,j}}} \frac{\gamma_{r,i}}{1 + \gamma_{r,i}}, \quad i = 1, \ldots, N. \tag{9}$$

Since the power value should be positive and limited, the following necessary condition must be satisfied:

$$\sum_{i=1}^{N} \frac{\gamma_{r,i}}{1 + \gamma_{r,i}} < 1. \tag{10}$$

When the left-hand side of (10) is close to 1, the optimal power levels may be too high to be sustainable. Moreover, the increase of the total power of MSs in one cell may adversely affect the surrounding cells and stimulate an increase of I. Therefore, it is necessary to impose the inequality

$$\sum_{i=1}^{N} \frac{\gamma_{r,i}}{1 + \gamma_{r,i}} \leq C_\delta < 1, \tag{11}$$

where $C_\delta < 1$, referred to as the *nominal capacity*, is a positive number.

From (9), (11), and some manipulation, the nominal capacity C_δ can be written as

$$C_\delta = \frac{P_U}{P_U + I + P_n}, \tag{12}$$

where $P_U = \sum_{i=1}^{N} P_i^*$. In general, P_U can be set by the service operator, imposing a target limit on the sum of the received signal power from all the MSs within the cell and limiting the interference from this cell to other cells. Hence, the nominal capacity can be determined by measuring $(I + P_n)$. Since I can be much larger than P_n in practice, in the following, we neglect P_n for simplicity of notation. As I is the sum of interfering power from a large number of MSs in other cells, it can be approximated by a Gaussian random variable. In each scheduling period, an estimate of I can be obtained by subtracting the sum of the intracell MS signal powers from the total received power measured at the BS and is known to the scheduler.

Since I is subject to variation, the nominal capacity C_δ varies with I. The proposed fair resource allocation scheme 1) guarantees a statistical delay bound for real-time traffic while taking into account the dynamics of C_δ and 2) provides a fairness bound for non-real-time traffic while making use of channel state information to achieve the multiuser diversity gain. The GPS-based fair scheduling discipline is used for both real-time and non-real-time traffic.

3.2 Resource Allocation for Real-Time Traffic

Real-time traffic is scheduled before non-real-time traffic in each scheduling period. The resource allocation is carried out jointly via fair scheduling and admission control. The admission control is to limit the total number of real-time traffic in the cell and to assign fixed weights to real-time traffic so that the required statistical delay bounds can be guaranteed.

Let MS i with real-time traffic be assigned a constant weight $\phi_{v,i}$, $i = 1, \ldots, N_v$, when it is admitted to the cell, where $\phi_{v,i}$ is related to the delay bound requirement of MS i. Let $B_i(k)$ denote the traffic amount (in bits) from flow i requested for transmission in slot k. Let $\gamma_{r,i}(k)$ denote the desired SIR of MS i in slot k and $S_{r,i}(k)$ the corresponding requested uplink resource amount. $\gamma_{r,i}(k)$ can be computed from $B_i(k)$ by

$$\gamma_{r,i}(k) = \left(\frac{E_b}{I_e}\right)_{r,i} \frac{B_i(k)}{f((E_b/I_e)_{r,i})TW}, \tag{13}$$

where $f((E_b/I_e)_{r,i})$ is an increasing function of the required $(E_b/I_e)_{r,i}$, which accounts for the effect of forward error control.[1] $S_{r,i}(k)$ is a share of the nominal capacity C_δ and can be written as

$$S_{r,i}(k) = \frac{\gamma_{r,i}(k)}{1 + \gamma_{r,i}(k)}. \tag{14}$$

Let $R_i(k)$ and $\gamma_i(k)$ be the allocated channel rate and SIR of MS i in slot k, respectively, where $\gamma_i(k) = R_i(k)(E_b/I_e)_{r,i}/W$. Let $S_{v,i}(k) = \gamma_i(k)/(1 + \gamma_i(k))$ be the allocated uplink resource for user i in slot k. Then, the objective of the scheduling is to find the resource allocation vector $[S_{v,1}, \ldots, S_{v,N_v}]$ and the corresponding rate vector $[R_1, \ldots, R_{N_v}]$ for all the N_v MSs, which can satisfy the GPS fairness constraint (3) (with weights $\phi_{v,i}$ and $\phi_{v,j}$ for all the N_v MSs) under the available nominal capacity C_δ.

Consider the MS i with Leaky-Bucket regulated traffic denoted by $(\rho_i, R_{m,i}, \sigma_i, D_i, L_i)$. MS i requires an effective bandwidth $R_{e,i}$ to guarantee its delay bound, which is given by [22]

$$R_{e,i} = \max\left\{\frac{R_{m,i}}{1 + \frac{D_i - 2T}{\sigma_i}(R_{m,i} - \rho_i)}, \rho_i\right\}, \tag{15}$$

where $2T$ is assumed to be the maximal delay due to signaling and scheduling. Note that $R_{e,i}$ $(\geq \rho_i)$ represents the minimum bandwidth requirement for MS i to achieve the delay bound D_i when it has continuous traffic backlog. An On-Off model can be used to characterize the bandwidth demand of MS i, where the traffic arrival rate is $R_{e,i}$ in the On-state and zero in the Off-state [22]. The probability of On-state is $P_{on,i} = \rho_i/R_{e,i}$. Given $R_{e,i}$, the minimum SIR requirement is $\gamma_{r,i} = \frac{R_{e,i}}{W}(\frac{E_b}{I_e})_{r,i}$ for MS i in the

1. In general, $f((E_b/I_e)_{r,i}) < 1$ since some redundant bits need to be transmitted for error control.

On-state. According to the fair scheduling discipline, the minimum resource amount that can be guaranteed to MS i in each scheduling period is proportional to its weight $\phi_{v,i}$. Without loss of generality, let $\phi_{v,i} = \gamma_{r,i}/(1+\gamma_{r,i})$. The scheduling scheme, named *static-weight* code-division GPS (SW-CDGPS), is outlined as follows: First, $B_i(k)$ is converted to the bandwidth requested in terms of $S_{r,i}(k)$ for each MS. Second, the scheduler checks if the total bandwidth requests exceed the nominal capacity C_δ: If it does not, then each MS can be granted the requested bandwidth; otherwise, the resource allocation vector $[S_{v,1}, \ldots, S_{v,N_v}]$ for the N_v real-time traffic users is computed iteratively. In each iteration, a remaining capacity is calculated as the nominal capacity C_δ less the total bandwidth that has been granted to real-time traffic in previous iterations. A fair share of the remaining capacity is calculated for each MS whose requested bandwidth has not been granted, according to its GPS weight and the capacity constraint (11). For the user whose requested bandwidth is less than its fair share of the remaining capacity computed in any iteration, its request will be fully granted; otherwise, the user's $S_{v,i}$ will be determined in a later iteration. In the final iteration, each remaining MS will be given a fair share of the remaining capacity, but no more than its requested bandwidth. The implementation steps of SW-CDGPS algorithm are given in the Appendix.

The CAC can be developed based on the probability of delay bound violation for each MS. Let $P_{v,i}$ be the probability of delay bound violation for MS i, χ_i a random variable being 1 with probability $P_{on,i}$, and 0 with $1 - P_{on,i}$. Then, $P_{v,i}$ can be represented by

$$\begin{aligned} P_{v,i} &= P\left\{\frac{\phi_{v,i} C_\delta}{\phi_{v,i} + \sum_{j \neq i} \phi_{v,j}\chi_j} < S_{r,i}\right\} \\ &= P\left\{\frac{1}{1+Y} < \phi_{v,i} + \sum_{j \neq i} \phi_{v,j}\chi_j\right\}, \end{aligned} \tag{16}$$

where $Y = I/P_U$. To estimate $P_{v,i}$, we first obtain a loose upper-bound by letting $\chi_j = 1$ in (16). This is equivalent to the worst case that all the users are in the On-state and the delay bound violation occurs when $\sum_{j=1}^{N_v} \phi_{v,j} > C_\delta$. Therefore, we have

$$\begin{aligned} P_{v,i} &\leq \left\{\frac{1}{1+Y} < \sum_{j=1}^{N_v} \phi_{v,j}\right\} \\ &= 1 - F_Y\left(\frac{1}{\sum_{j=1}^{N_v} \phi_{v,j}} - 1\right), \end{aligned} \tag{17}$$

where $F_Y(y)$ is the cumulative distribution function (cdf) of Y. Since I is approximated by a Gaussian random variable and P_U is a constant, Y is also approximately Gaussian.

The CAC based on the loose delay violation bound (17) is 1) to admit a new MS if

$$\sum_{j=1}^{N_v+1} \phi_{v,j} \leq \frac{1}{1 + F_Y^{-1}(1 - L_i)}, \quad \forall i, \tag{18}$$

where $F_Y^{-1}(\cdot)$ is the inverse function of $F_y(\cdot)$, and 2) to reject the user otherwise. The CAC scheme is conservative because statistical multiplexing is not taken into account. Estimation of $P_{v,i}$ using 1) the Gaussian approximation or 2) the Chernoff bound gives a more optimistic CAC scheme [24].

3.3 Scheduling Scheme for Non-Real-Time Traffic

For non-real-time traffic without stringent delay requirements, throughput can be made beneficial by dynamically adjusting the assigned weights according to channel conditions. Let the variable weight $w_{d,i}(k)$ for MS i in slot k be defined by

$$w_{d,i}(k) = \phi_{d,i}\left(1 + \alpha \frac{X_{i0}(k)}{\sum_{l=1}^{N_d} X_{l0}(k)}\right), \tag{19}$$

where α is a nonnegative real number which is decided by the required fairness bound (to be discussed later). The weight is a function of multipath fading channel gains between all the MSs and their home BS (BS 0) during scheduling period k and dynamically adjusted from time to time. Therefore, this scheduling scheme is named the *dynamic-weight* code-division GPS (DW-CDGPS) fair scheduling scheme.

In each slot, the DW-CDGPS scheduler performs the same resource allocation procedure as in the SW-CDGPS described in Section 3.2, except that the N_v, $\phi_{v,i}$, and C_δ in the SW-CDGPS scheme are replaced by N_d, $w_{d,i}(k)$, $i = 1, \ldots, N_d$, and $C'_\delta(k)$, which is the remaining capacity for non-real-time traffic after real-time traffic has been scheduled. If all users are greedy, then the resource allocated by the DW-CDGPS to each MS in a slot is $C'_\delta(k) w_{d,i}(k)/\sum_{l=1}^{N_d} w_l(k)$, in contrast to $C_\delta \phi_{v,i}/\sum_{l=1}^{N_v} \phi_{v,l}$ in SW-CDGPS.

To derive the fairness bound, let $e(k)$ be the remaining capacity for the greedy users in the kth slot. The resource allocated to user i in the slot is

$$S_{d,i}(k) = e(k) w_{d,i}(k) / \sum_{l=1}^{N_d} w_{d,l}(k).$$

Consider an interval (t_1, t_2). Let $S_i(t_1, t_2) = \sum_{k=t_1}^{t_2} S_{d,i}(k)$. For any two greedy users i and m,

$$\begin{aligned} F_{im} &= \frac{\left|\frac{S_i(t_1,t_2)}{\phi_{d,i}} - \frac{S_m(t_1,t_2)}{\phi_{d,m}}\right|}{S_i(t_1,t_2)/\phi_{d,i}} \\ &= \left|\frac{\sum_{k=t_1}^{t_2} e(k)\alpha \frac{X_{i0}(k) - X_{m0}(k)}{\sum_{l=1}^{N_d} X_{l0}(k)}}{\sum_{k=t_1}^{t_2} e(k)\left[1 + \alpha \frac{X_{i0}(k)}{\sum_{l=1}^{N_d} X_{l0}(k)}\right]}\right|. \end{aligned} \tag{20}$$

For short-term fairness, a small $(t_2 - t_1)$ value is assumed and multipath fading factor $X_{i0}(k)$ is considered to be invariant during (t_1, t_2) and denoted by $X_{i0}, i = 1, 2, \ldots, N_d$. Then, the short-term fairness can be approximated by

$$\begin{aligned} F_{im} &\approx \left|\frac{[\sum_{k=t_1}^{t_2} e(k)]\alpha \frac{X_{i0} - X_{m0}}{\sum_{l=1}^{N_d} X_{lj}}}{[\sum_{k=t_1}^{t_2} e(k)]\left[1 + \alpha \frac{X_{i0}}{\sum_{l=1}^{N_d} X_{lj}}\right]}\right| \\ &= \left|\frac{\alpha(X_{i0} - X_{m0})}{X_{N_d} + \alpha X_{i0}}\right| < \frac{\alpha |X_{i0} - X_{m0}|}{X_{N_d}}, \end{aligned} \tag{21}$$

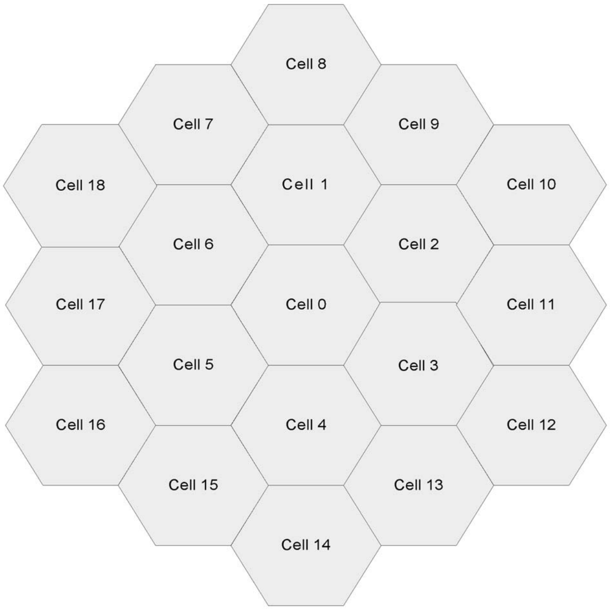


Fig. 2. Hexagonal layout of cells.

where $X_{N_d} = \sum_{l=1}^{N_d} X_{l0}$. From (21), it can be seen that the short-term fairness index is a random variable. By adjusting the parameter α, an arbitrary small fairness bound as specified in (6) can be achieved (as will be seen in the simulation results). In an extreme case, when $\alpha = 0$, the scheme reduces to the static-weight scheduling scheme and strict GPS fairness can be achieved. The larger the α is, the looser the statistical bound can be guaranteed. It should be noted that tight delay bounds normally required by real-time traffic cannot be guaranteed by the DW-CDGPS scheme (for $\alpha > 0$) since the allocated bandwidth for a user fluctuates when multipath channel gain changes.

4 Capacity Analysis

In this section, analytical results are presented for the potential performance gain by the dynamic-weight scheme, compared to the static-weight scheme, for non-real-time traffic. Consider a two-tier hexagonal layout of cells with a unit cell radius, as shown in Fig. 2. MSs are randomly located in the networks with a uniform density of $\rho = 2N/3\sqrt{3}$. An MS always selects the best BS that has the minimum signal attenuation due to path loss and shadowing. Omnidirectional antennas are used in both MSs and BSs. Consider a test cell, cell 0, which receives intercell interference only from its 18 surrounding cells in the first and second tiers. Under the assumption that all the N MSs in each cell are homogeneous greedy data users with preassigned weights $\phi_{d,i} = 1$, $i = 1, \ldots, N$, we derive close form expressions of the mean and variance of the intercell interference power I, which can be used to obtain the distribution of the nominal capacity. The statistics of I and C_δ will be compared under different scheduling schemes with different fairness bounds.

In general, the mean and variance of I at the BS of cell 0 are approximately given by [10]

$$E[I] = A_0(\mu,\sigma)\sum_{i=1}^{N} E\left[P_i \frac{X_{i0}}{X_{ij}}\right], \quad (22)$$

$$V[I] = A_1(\mu,\sigma)\sum_{i=1}^{N} E\left[P_i \frac{X_{i0}}{X_{ij}}\right]^2 - A_2(\mu,\sigma)\sum_{i=1}^{N} E^2\left[P_{ij} \frac{X_{i0}}{X_{ij}}\right], \quad (23)$$

where $A_0(\mu,\sigma)$, $A_1(\mu,\sigma)$, and $A_2(\mu,\sigma)$ are functions of path loss, shadowing, and the distribution of MS location in the 18 surrounding cells, which are assumed to be independent of the multipath fading. Consider an MS in cell j (one of the 18 neighboring cells), generating intercell interference to the target cell. Let r_0 be the distance from the MS to BS 0 and r_j the distance from the MS to its home BS (BS j). Then, $A_0(\mu,\sigma)$, $A_1(\mu,\sigma)$, and $A_2(\mu,\sigma)$ are given by [11]

$$A_0(\mu,\sigma) = e^{(\sigma \ln(10)/10)^2} \int\int \left(\frac{r_j}{r_0}\right)^{\mu} Q\left[\sqrt{2\sigma^2}\frac{\ln(10)}{10} - \frac{10\mu}{\sqrt{2\sigma^2}}\log_{10}\left(\frac{r_0}{r_j}\right)\right]\rho' dA, \quad (24)$$

$$A_1(\mu,\sigma) = e^{(\sigma \ln(10)/5)^2} \int\int \left(\frac{r_j}{r_0}\right)^{2\mu} Q\left[\sqrt{2\sigma^2}\frac{\ln(10)}{5} - \frac{10\mu}{\sqrt{2\sigma^2}}\log_{10}\left(\frac{r_0}{r_j}\right)\right]\rho' dA, \quad (25)$$

$$A_2(\mu,\sigma) = e^{2(\sigma \ln(10)/10)^2} \int\int \left(\frac{r_j}{r_0}\right)^{2\mu} Q^2\left[\sqrt{2\sigma^2}\frac{\ln(10)}{10} - \frac{10\mu}{\sqrt{2\sigma^2}}\log_{10}\left(\frac{r_0}{r_j}\right)\right]\rho' dA, \quad (26)$$

where $\rho' = \rho/N$, A is the area of the considered cells, and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$. Given $\mu = 4$ and $\sigma = 8$dB, it can be obtained numerically that $A_0(4,8) = 0.659$, $A_1(4,8) = 0.223$, and $A_2(4,8) = 0.04$.

Let P_i^s and P_i^d denote the allocated received power under the static-weight scheme and the dynamic-weight scheme and I_s and I_d be the intercell interference under the static-weight scheme and the dynamic-weight scheme, respectively. Then,

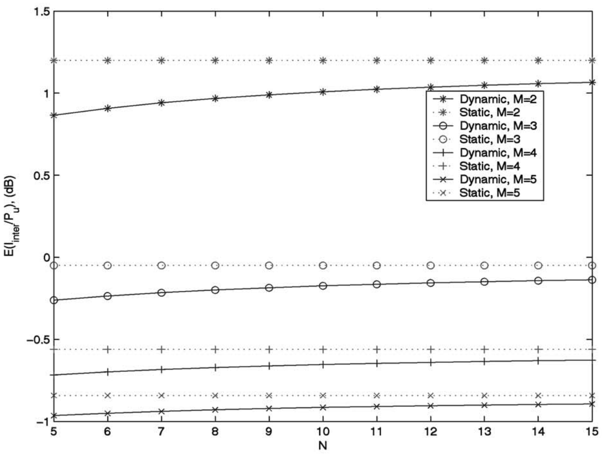
$$P_i^s = P_U/N, \quad P_i^d = P_U\frac{1 + \alpha X_{ij}/X_N}{N + \alpha}. \quad (27)$$

Substituting P_i in (22) and (23) by P_i^s and considering that $P_U = \sum_{i=1}^{N} P_i$; X_{i0}, X_{ij}, $i = 1, \ldots, N$, are i.i.d., we have, for $M > 1$,

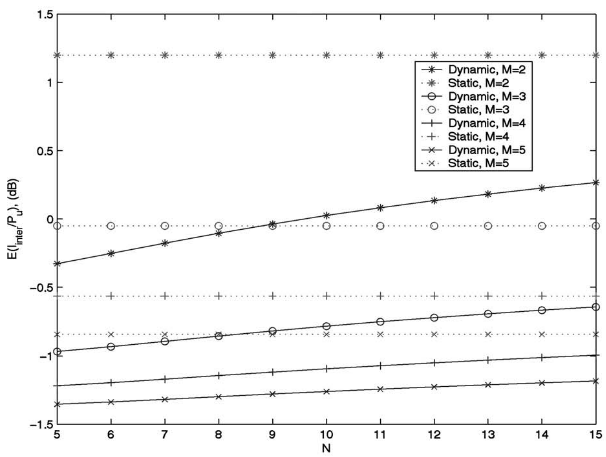
$$E\left[\frac{I_s}{P_U}\right] = A_0(\mu,\sigma)\frac{M}{M-1}, \quad (28)$$

$$V\left[\frac{I_s}{P_U}\right] = A_1(\mu,\sigma)\frac{M(M+1)}{N(M-1)(M-2)} - A_2(\mu,\sigma)\frac{M^2}{N(M-1)^2}. \quad (29)$$

For $M = 2$, $V[I_s/P_U]$ is infinite, which is the case that the transmission power of MSs can increase to infinite to compensate for deep fading. In practice, since the



(a)



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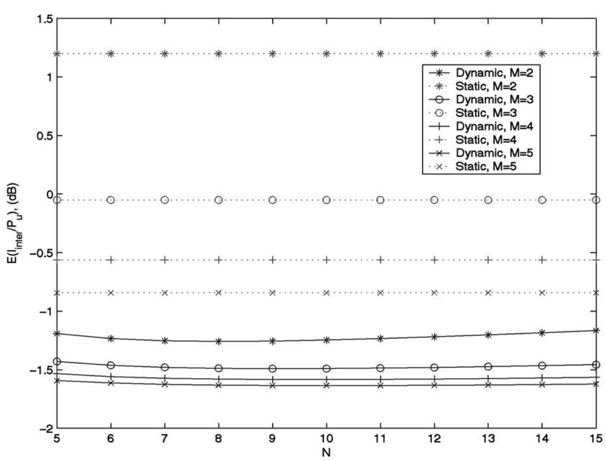


(c)

Fig. 3. $E(I/P_U)$ for different number of resolvable paths under SW-CDGPS and DW-CDGPS. (a) $\alpha = 1$. (b) $\alpha = 10$. (c) $\alpha = 100$.

transmission power of the MSs is limited, $V[I_s/P_U]$ is also limited. The value of $V[I_s/P_U]$ for $M = 2$ can be evaluated numerically under the constraint of limited transmitted power from the MSs [10].

For the dynamic-weight scheme, substituting P_i in (22) and (23) by P_i^d, it can be derived that [24]

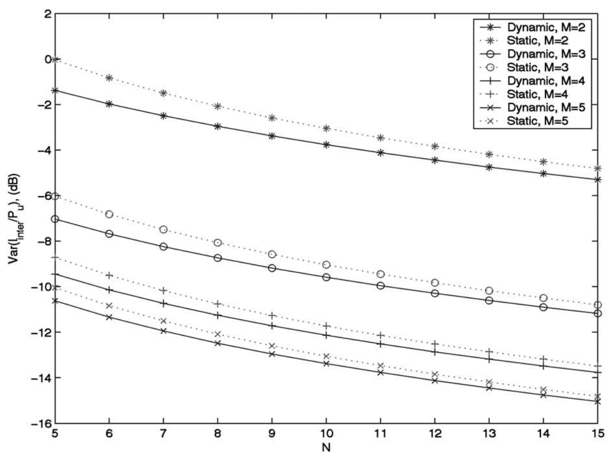
$$E\left[\frac{I_d}{P_U}\right] = A_0(\mu,\sigma)N\left(\frac{M}{(N+\alpha)(M-1)} + \frac{\alpha M}{(N+\alpha)(NM-1)}\right), \tag{30}$$

$$\begin{aligned} V\left[\frac{I_d}{P_U}\right] &= A_1(\mu,\sigma)NM(M+1) \\ &\left[\frac{1}{(N+\alpha)^2(M-1)(M-2)} + \frac{\alpha^2}{(N+\alpha)^2(NM-1)(NM-2)}\right. \\ &\left. + \frac{2\alpha}{(N+\alpha)^2(M-1)((N-1)M-1)}\right] \\ &- A_2(\mu,\sigma)N\left(\frac{M}{(N+\alpha)(M-1)} + \frac{\alpha M}{(N+\alpha)(NM-1)}\right)^2. \end{aligned} \tag{31}$$

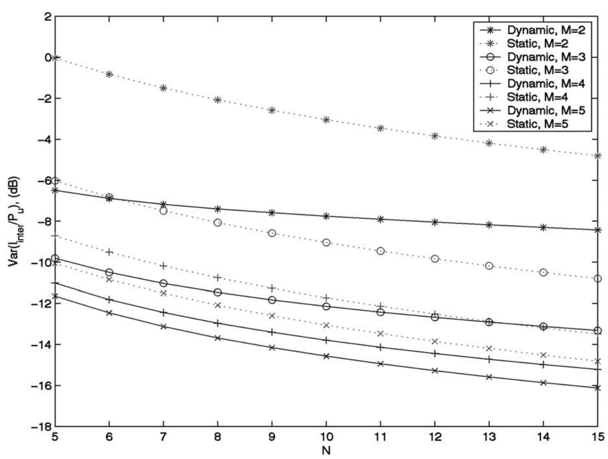
Figs. 3 and 4 show the mean and variance of the intercell interference under the SW-CDGPS and DW-CDGPS schemes. In each figure, the effects of the number of resolvable paths (M) and the number of MSs (N) in each cell are shown. Figs. 3a and 4a show the case of $\alpha = 1$. In this case, the DW-CDGPS can support a tight statistical fairness bound. It can be seen that both the mean and variance of the intercell interference can be reduced by the dynamic-weight fair scheduling scheme, with the trade-off of short-term fairness. Figs. 3b and 4b show the case of $\alpha = 10$, and Figs. 3c and 4c show the case of $\alpha = 100$. It can be seen that the larger the α is, the lower the intercell interference can be under the dynamic-weight scheme.

Based on the statistics $Y = I/P_U$, the pdf of the nominal capacity C_δ is $f_{C_\delta}(x) = \frac{1}{x^2} f_Y\left(\frac{1-x}{x}\right)$, where $f_Y(y)$ is the pdf of the Gaussian random variable Y with mean and variance given by (30)-(31), or (28)-(29). In order to illustrate the capacity gain achieved by the dynamic-weight scheme, we define $C_{\delta,90\%}$ as a deterministic variable such that $P\{C_\delta > C_{\delta,90\%}\} = 90\%$. $C_{\delta,90\%}$ can be seen as a statistical lower bound of the nominal capacity C_δ. Fig. 5 shows the $C_{\delta,90\%}$ for $\alpha = 100$. It can be seen that the nominal capacity can be increased by using the dynamic-weight scheme instead of the static-weight scheme. In the case of $\alpha = 100$, for instance, the capacity gain is about 10% when $M = 5$ and about 60% when $M = 2$. For both schemes, the nominal capacity increases with M. This is because, when the number resolvable paths increases, the variability of channel fading decreases, which in turn translates to lower mean and variance of intercell interference. It can also be seen that the nominal capacity $C_{\delta,90\%}$ increases with N. This is mainly caused by the reduced variance of intercell interference when N increases.

Given the distribution of C_δ, the average achievable data throughput can be evaluated as follows: Since MS i data throughput is proportional to the achieved SIR γ_i, we only need to calculate the average γ_i for any MS i in cell 0. Without loss of generality, consider MS 1. Let γ_1^s and γ_1^d be the SIR of MS 1 in cell 0 under the static-weight scheme and the dynamic-weight scheme, respectively. Then, we have $\gamma_1^s = \frac{C_\delta}{N - C_\delta}$ and $\gamma_1^d = \frac{X_{10}C_\delta}{X_{(N-1)} + \delta X_{10}}$, where $X_{(N-1)} = \sum_{i=2}^{N} X_{i0}$. Since X_{i0}, $i = 1, \ldots, N$, are i.i.d., $X_{(N-1)}$ is independent of X_{10}. The pdf of $X_{(N-1)}$ is



(a)



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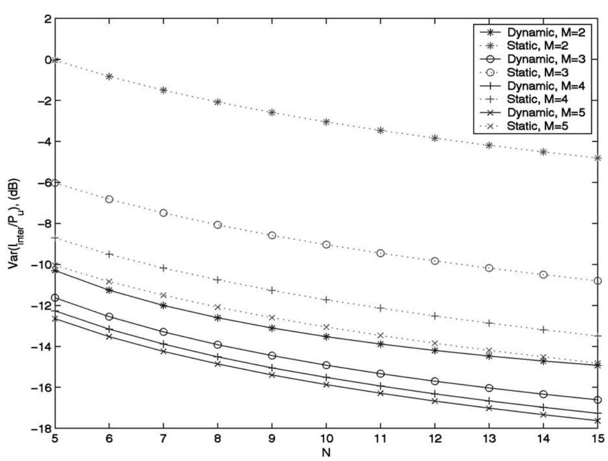


(c)

Fig. 4. $Var(I/P_U)$ for different number of resolvable path under SW-CDGPS and DW-CDGPS. (a) $\alpha = 1$. (b) $\alpha = 10$. (c) $\alpha = 100$.

$$f_{X_{N-1}}(x) = \frac{M^{(N-1)M}}{((N-1)M-1)!} x^{(N-1)M-1} e^{-Mx} U(x).$$

With the pdf of C_δ, X_{10}, and $X_{(N-1)}$, the expected values of γ_1^s and γ_1^d can be obtained by numerical integration. Fig. 6 shows the average γ_1^s and γ_1^d multiplied by N for different M and N. It can be seen that the dynamic-weight scheme can achieve higher average data throughput than the static-weight scheme. When M increases from 2 to 5, the achievable average throughput increases significantly under the static scheme, whereas it only increases slightly under the dynamic scheme. This is because the dynamic scheme can make use of multiuser diversity to reduce the intercell interference and to improve the average data throughput, even when M is small. It should be noticed that DW-CDGPS scheme is not suitable for real-time traffic since it is difficult to guarantee the required minimum bandwidths and delay bounds for real-time traffic when the weights are adjusted with channel condition.

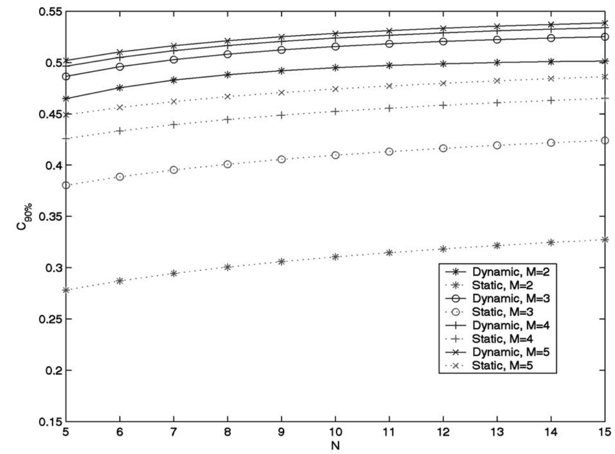


Fig. 5. Nominal capacity under SW-CDGPS and DW-CDGPS ($\alpha = 100$).

5 Simulation Results

In this section, simulation results are presented to demonstrate the performance of the proposed resource allocation schemes in terms of delay, throughput, and GPS fairness. The target cell and its 18 neighboring cells in the first and second tiers are simulated. MSs are uniformly distributed in the service area. Each Rayleigh fading channel with a maximum Doppler shift of 5 Hz is generated using the Jake's simulator [23]. Table 1 lists the simulation parameters.

In the first simulation, each cell has 12 homogeneous greedy data users. Three cases, where $\alpha = 1, 10, 100$, respectively, are simulated for the DW-CDGPS scheme, compared to the SW-CDGPS scheme with static weight. The fairness index F_{im} is measured once every 20 slots in the simulation run for a total of 30,000 slots. I/P_U of cell 0 is measured for each slot. Fig. 7 shows the complementary cumulative distribution of the fairness indexes for different α. It can be seen that the statistical fairness bound can be regulated effectively by adjusting α. Table 2 shows the mean and variance of I/P_U for different schemes. It can be seen that the DW-CDGPS schemes can decrease the mean and variance of the intercell interference compared to the SW-CDGPS scheme, as predicted by the analytical results shown in Figs. 3 and 4. Note that the $E[I/P_U]$ values shown in the table agree with those of the corresponding points ($N = 12, M = 3$) in Fig. 3, while the $V[I/P_U]$ values obtained in the simulation are lower than the corresponding points in Fig. 4. This is because the analytical results are asymptotic

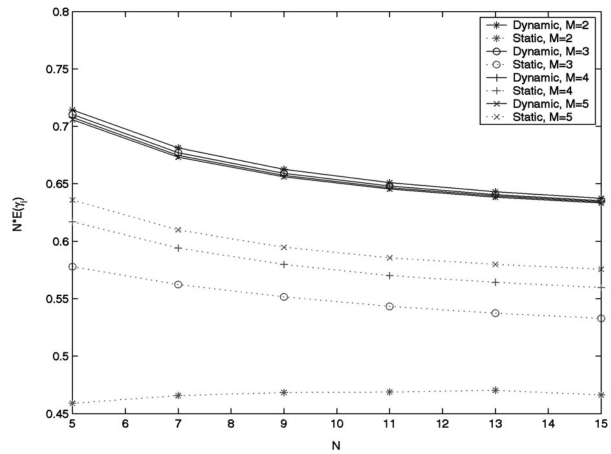


Fig. 6. Average achievable SIR, under SW-CDGPS and DW-CDGPS ($\alpha = 100$).

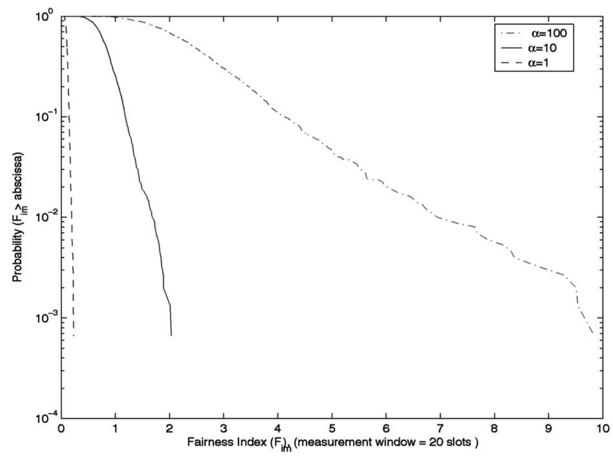


Fig. 7. Comparison of statistical fairness bounds ($\alpha = 1, 10, 100.$).

and take into account the variance of user locations, whereas the simulation results are obtained from snap-shot simulation during which MS locations are nearly fixed. However, it can be seen that the amount of decrease in $E[I/P_U]$ and $V[I/P_U]$ of each DW-CDGPS scheme compared to the SW-CDGPS are close to that shown in the figures. In other words, the simulated capacity gain agrees with the analysis quite well.

In the second simulation, 12 homogeneous Poisson data traffic flows are simulated and delay and throughput performances of users in cell 0 are compared. For the DW-CDGPS, α is set to be 100, corresponding to a large fairness bound. Fig. 8 shows the throughput comparison of the DW-CDGPS and SW-CDGPS. The traffic load is defined to be the sum of average arrival rates of all data flows. The throughput and traffic load are normalized by C, which is defined as the maximal achievable throughput under SW-CDGPS when traffic load is high. It is shown that the DW-CDGPS scheme can improve the maximal uplink throughput significantly compared to the SW-CDGPS scheme. The throughput gain is seen only when traffic load is high since when the traffic load is low, the throughput equals to the total traffic arrival rate. Fig. 9 shows the average delays achieved by the two schemes. It can be seen that, when the traffic load is high (around 1), the average delay can be reduced up to 70 percent, by DW-CDGPS as compared to the SW-CDGPS. This implies that the short-term unfairness introduced by the DW-CDGPS can actually benefit the delay performance in the uplink when traffic load is high due to a high throughput that can be achieved. When traffic load is low, the delay performance can still be improved slightly.

In the third simulation, the admissible region and QoS performance of real-time traffic are tested. The proposed CAC scheme is tested first. For a simple example, assume there are two classes of traffic. For the first class traffic, $\gamma_{1,0} = 0.016$, $P_{on,1} = 0.4$, and $L_1 = e^{-4}$. For the second class, $\gamma_{1,0} = 0.032$, $P_{on,1} = 0.5$, and $L_1 = e^{-5}$. Fig. 10 shows the capacity region under different CAC criteria. For comparison, we also include a criterion based on the average rate of each user, namely, average-rate CAC, i.e., an MS is admitted if $\sum_{j=1}^{N} \phi_j P_{on,j} \leq \frac{1}{1+F_Y^{-1}(1-L_i)}$, $\forall i$. It can be seen that the admissible region obtained by Gaussian approximation is close to that by Chernoff bound approximation. The Gaussian approximation-based CAC is more conservative than the Chernoff bound-based CAC. As expected, the average-rate approach yields an overestimated admissible region, while the effective-bandwidth based CAC is the most conservative.

We then simulate the voice and VBR video flows. Each voice flow is generated by using an On-Off model, where the activity factor is 0.4 and packets are generated in the ON-state at a constant rate $R_{v,i} = 8\,\text{kbps} = 100$ packets/second with the packet length of 80 bits. The parameters of the Leaky-Bucket regulator for any voice traffic flow (say flow i) are: $\rho_i = 3.2$ kbps, $R_{m,i} = 8$ kbps, $\sigma_i = 8$ kbs, $D_i = 20$ ms, and $L_i = e^{-4} = 0.0183$. From (15), we can have $R_{e,i} = R_{v,i}$. Then, the amount of allocated resources is $\gamma_{r,i} = 2/125$, which results in the weight assigned to each voice flow being $\phi_{v,i} = 0.0157$. The VBR Video traffic is generated by using an 8-state MMPP

TABLE 1
The Simulation Parameters

symbol	value	symbol	value
μ	4	σ	4 dB
W	5 Mbps	T	10 ms
$(E_b/I_e)_{r,i}$	10 dB	$f((E_b/I_e)_{r,i})$	1

TABLE 2
Statistics of I/P_U Under Static-Weight and Dynamic-Weight Scheduling

Statistics (dB)	Static Weight	Dynamic Weight		
		$\alpha = 1$	$\alpha = 10$	$\alpha = 100$
$E[I/P_U]$	-0.0989	-0.1990	-0.7310	-1.443
$V[I/P_U]$	-12.89	-13.40	-16.61	-20.93

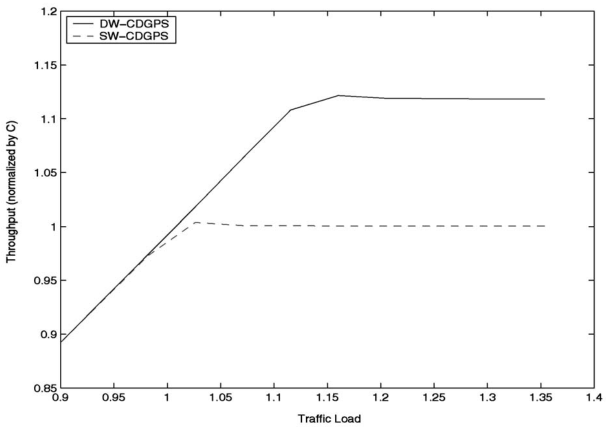


Fig. 8. Throughput comparison: SW-CDGPS and DW-CDGPS ($\alpha = 100$).

model and a Leaky-Bucket regulator. The average duration in each state is $40ms$, which is equivalent to the length of one frame of the video sequence with frame rate of 25 frames/second. The parameters of the Leaky-Bucket regulator for any video traffic flow (say flow i) are: $\rho_i = 90$ kbps, $R_{m,i} = 192$ kbps, $\sigma_i = 14$ kilobits, $D_i = 80$ ms, and $L_i = e^{-4} = 0.0183$. The effective bandwidth of each video traffic flow is obtained as $R_{e,i} = 143$ kbps, with $P_{on,i} = \rho_i / R_{e,i} = 0.63$. The weight assigned to the video flow is $\phi_{v,i} = 0.2866$. Mixed video and voice traffic flows are simulated to demonstrate the delay performance in terms of statistical delay bound. Fig. 11a shows the distribution of delay in the case of eight voice and two video flows. This case corresponds to the point within the admissible region of Chernoff bound-based CAC. It can be seen that the statistical delay bounds of both voice and video are satisfied. Fig. 11b shows the case of two video and 14 voice flows. As can be seen, the delay performances of both classes of traffic are close to the required statistical delay bounds. This verifies that the case corresponds to the point at the boundary of the admissible region. Table 3 shows the delay of each flow in this case. It is shown that all the real-time users achieve the required statistical QoS. Fig. 11c shows the case of three video traffic flows, which is not admissible according to any criteria except for the average-rate based one. It can be seen that the delay performance, $P\{\tau > 0.08\} > 0.2$, is worse than the requirement.

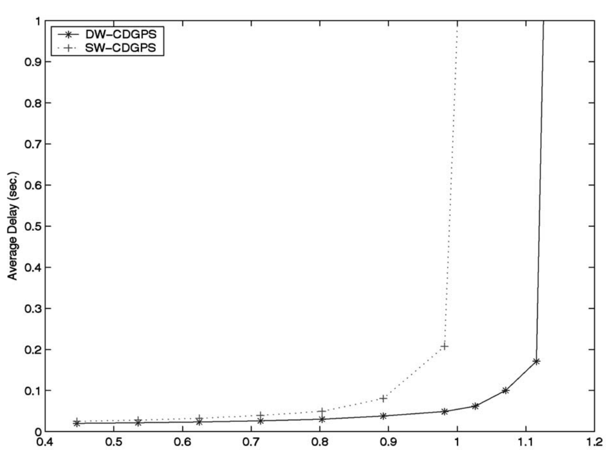
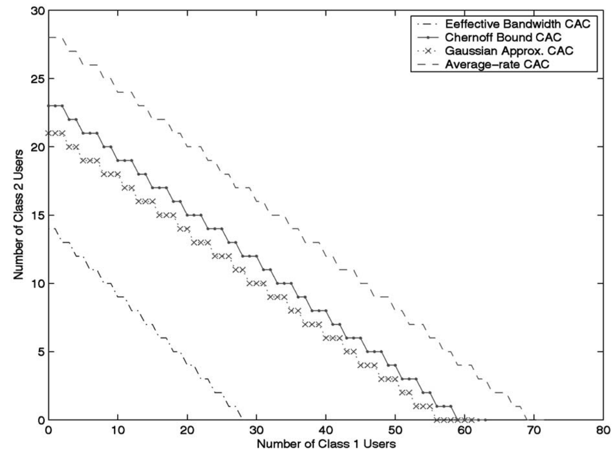


Fig. 9. Average delay comparison.



Fg. 10. Admissible region for two classes of real-time traffic.

6 Conclusion

An efficient dynamic fair resource allocation scheme has been proposed for supporting multimedia traffic in the uplink of wideband CDMA cellular networks with QoS satisfaction. The analysis and simulation results show that, in a multipath fading environment, the proposed scheme can reduce the intercell interference, increase the network capacity, guarantee a statistical delay bound for real-time traffic and a statistical fairness bound for non-real-time users. The proposed scheme allows for a flexible trade-off between the generalized processor sharing (GPS) fairness and efficiency in resource allocation and is an effective way to maximize the radio resource utilization under the fairness and QoS constraints.

Appendix

SW-CDGPS Resource Allocation Algorithm

The SW-CDGPS algorithm is developed to find the resource allocation vector $(S_{v,1}, S_{v,2}, \ldots, S_{v,N_v})$ and the corresponding rate vector $(R_1, R_2, \ldots, R_{N_v})$. Without loss of generality, let $\phi_i = \phi_{v,i}$, G_i be the guaranteed resource for user i

$$G_i = \frac{\phi_i C_\delta}{\sum_{j=1}^{N_v} \phi_j}. \tag{32}$$

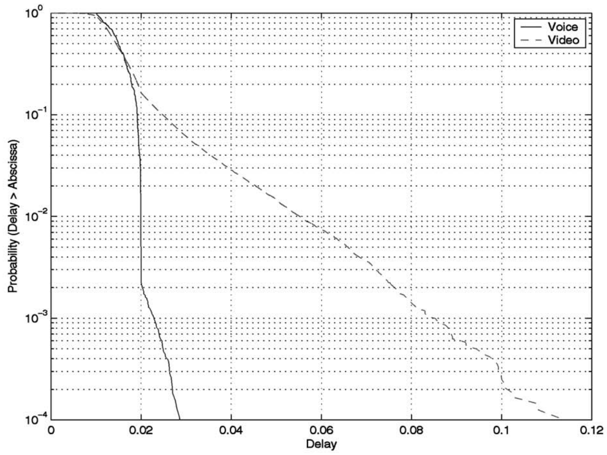
C_n denotes the remaining capacity available in the nth iteration, $\mathcal{B}$ is a set of users whose bandwidth request is larger than its fair share of C_n in each iteration. The algorithm operates as follows:

Step 1. Compute $S_{r,i}(k)$ in slot k, $i = 1, \ldots, N$, by (13) and (14).

Step 2. Determine $S_{v,i}(k)$, $i = 1, \ldots, N_v$, as follows:

2.1. If

$$\sum_{i=1}^{N_v} S_{r,i}(k) < C_\delta,$$



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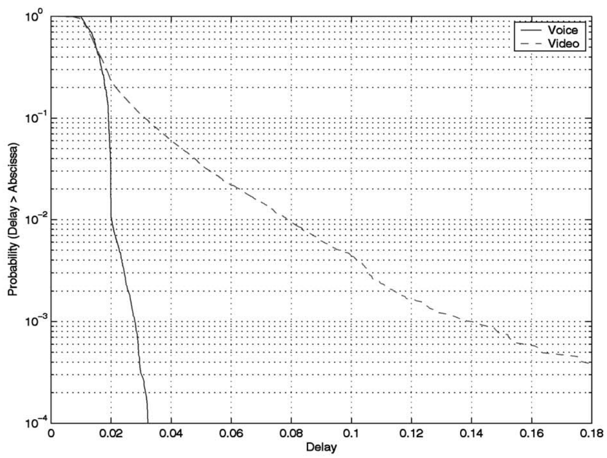

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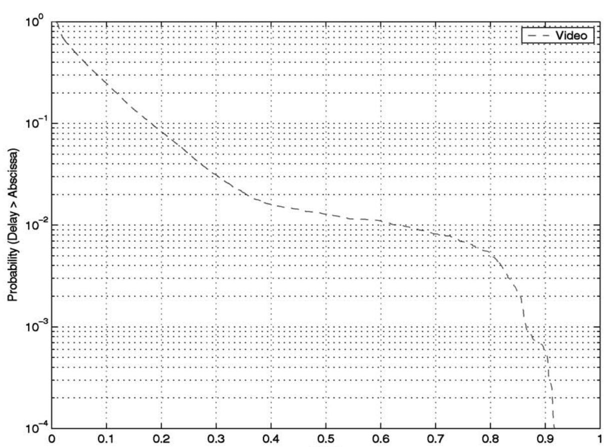

(c)

Fig. 11. Distribution of delay (eight voice users, two video users). (a) Eight voice users, two video users. (b) Fourteen voice users, two video users. (c) Three video users.

then $S_{v,i}(k) = S_{r,i}(k)$, $i = 1, \ldots, N_v$, and go to Step 3; Otherwise, go to Step 2.2.

2.2. If any $S_{r,i}(k) \leq G_i$, then $S_{v,i}(k) = S_{r,i}(k)$, and let the set $\mathcal{B} = \{j : S_{r,j}(k) > G_j\}$.

TABLE 3
Statistical Delay Bounds of Mixed Voice/Video Traffic (Flows 1-14 Are Voice Traffic and Flows 15-16 Are Video Traffic)

Flow ID	Average Delay (s)	Maximal Delay (s)	$P_{v,i}$
1	0.0152	0.0299	0.0119
2	0.0149	0.0333	0.0100
3	0.0152	0.0343	0.0097
4	0.0156	0.0374	0.0102
5	0.0146	0.0385	0.0152
6	0.0146	0.0296	0.0068
7	0.0149	0.0370	0.0082
8	0.0153	0.0302	0.0120
9	0.0147	0.0351	0.0101
10	0.0151	0.0293	0.0052
11	0.0148	0.0354	0.0121
12	0.0147	0.0357	0.0106
13	0.0151	0.0391	0.0141
14	0.0146	0.0363	0.0093
15	0.0187	0.204	0.0076
16	0.0190	0.207	0.0096

2.3. Perform the following iteration until all $S_{v,j}(k)$, $j \in \mathcal{B}$, are assigned.

In the nth iteration ($1 \leq n < N_v$), let C_n be

$$C_n = C_\delta - \sum_{i \notin \mathcal{B}} S_{v,i}(k). \qquad (33)$$

If, for any $i \in \mathcal{B}$, $S_{r,i}(k) \leq \phi_i C_n / \sum_{j \in \mathcal{B}} \phi_j$, then $S_{v,i}(k) = S_{r,i}(k)$, remove i from $\mathcal{B}$ and continue to the $(n+1)\mathrm{th}$ iteration; else, let $S_{v,i}(k) = \phi_i C_n / \sum_{j \in \mathcal{B}} \phi_j$ for all $i \in \mathcal{B}$ and stop the iteration.

Step 3. The allocated channel rate to user i can be determined by

$$R_i(k) = \frac{W S_{v,i}(k)}{(1 - S_{v,i}(k))(E_b/I_e)_{r,i}}. \qquad (34)$$

Acknowledgments

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