A Dynamic Code Assignment Algorithm for Quality of Service in 3G Wireless Networks

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Abstract—Emerging Third Generation (3G) wireless standards promise a “last-mile” solution capable of supporting mobile, wireless Internet service. The Third Generation Partnership Proposal (3GPP) Wideband Code Division Multiple Access (WCDMA) standard will support data rates up to 2 Mbps with Orthogonal Variable Spreading Factor (OVSF) codes. This paper presents a dynamic OVSF code assignment algorithm that efficiently shares a WCDMA downlink between data traffic sources with different QoS requirements. Our simulation results verify that the algorithm functions as desired. The QoS guarantees for high QoS traffic are protected, and best effort traffic is able to utilize available bandwidth.

I. INTRODUCTION

Emerging Third Generation (3G) wireless standards promise a “last-mile” solution capable of supporting mobile, wireless Internet service. 3G standards will support data rates up to 2 Mbps, rivaling the speed of wired technologies like cable modems or Digital Subscriber Lines (DSL). By implementing both circuit and packet switching, 3G will provide mobile subscribers with wireless voice and “always-on” data service. 3G systems will utilize error correction coding and bandwidth allocation to support different Quality of Service (QoS) levels.

The Third Generation Partnership Proposal (3GPP) Wideband Code Division Multiple Access (WCDMA) standard will support data rates up to 2 Mbps with Orthogonal Variable Spreading Factor (OVSF) codes. The authors in [1] proposed a method of generating orthogonal spreading codes with different lengths. These variable spreading factor codes provide a means of bandwidth allocation in a CDMA system. Each user is assigned a single spreading code, with a spreading factor (SF) corresponding to the required data rate. The properties of OVSF codes limit which codes can be simultaneously assigned. As a result, the assignment of OVSF codes has a significant impact on efficient resource utilization.

This paper presents a dynamic OVSF code assignment algorithm that efficiently shares a WCDMA downlink between data traffic sources with different QoS requirements. Traffic is classified as either improved QoS or best effort. Improved QoS traffic is initially assigned a set of OVSF codes that support different data rates. The bandwidth allocated to improved QoS traffic is dynamically adjusted, based upon offered traffic load, by selecting an appropriate code from the assigned set. Best effort traffic can utilize available bandwidth, when improved QoS traffic is not transmitting at peak data rates, by transmitting on an orthogonal code. The algorithm exploits the bursty nature of data traffic to effectively share wireless resources between improved QoS and best effort traffic sources. As such, it improves upon previously published OVSF code assignment algorithms [2][3][4]. Initial simulations of the algorithm demonstrate that it makes efficient use of the available wireless bandwidth, while protecting higher QoS traffic from best effort traffic.

The rest of the paper is organized as follows. We begin with an overview of 3G cellular communications and the 3GPP WCDMA standard in Section II. Section III discusses the tree structured method of generating OVSF codes. Next, Section IV gives an overview of existing OVSF code assignment algorithms. Our proposed dynamic code assignment algorithm is presented in Section V. Finally, Section VI presents simulation results that verify correct operation of the algorithm and examine the algorithm efficiency.

II. THIRD GENERATION CELLULAR COMMUNICATIONS

The emerging 3G wireless standards are being designed with the flexibility to support a variety of devices and applications. Current Second Generation (2G) cellular systems are primarily voice systems, with data rates up to 19.2 Kbps [5]. These include Global System for Mobile Communications (GSM), IS-136 (TDMA) and IS-95 (CDMA). 3G wireless systems will provide data rates up to 384 kbps in wide coverage areas, and 2 Mbps in local coverage areas [6][7]. These data rates will support wireless applications such as Internet access, video conferencing, and other multimedia services. Additional 3G wireless goals include global mobility, support for circuit and packet switching, access via various radio interfaces, and support for different QoS levels [8][9][10].

The capabilities of the 3GPP WCDMA air interface proposal are representative of the emerging 3G proposals. WCDMA can support users with different bit error rate (BER) requirements, and data rates up to 2 Mbps. It has the capability to time multiplex streams, such as voice and data from the same source, over a single physical channel. WCDMA supports packet data transmission using both a shared access scheme and a dedicated access scheme. The WCDMA proposal uses orthogonal Direct Sequence Spread Spectrum (DSSS) codes, allowing several users to access each 5 MHz channel.

III. VARIABLE SPREADING FACTOR CODES

A tree-structured method of generating orthogonal codes with different lengths was proposed in [1]. These codes are called OVSF codes. The set of N codes at one level of the tree \{C_N(1)\cdots C_N(N)\} are generated from the previous level of the tree using Equation 1. A complete tree of codes is generated by recursively applying Equation 1. This is illustrated in Figure
algorithms. One factor contributing to the lack of published
algorithm.

Each level of the tree contains a set of orthogonal spreading
{1 for a three-level tree with seven spreading codes. The codes
\{C_2(1), C_2(2)\} are first generated from C_1(1). Then, codes
\{C_4(1) \cdots C_4(4)\} are generated from codes \{C_2(1), C_2(2)\}. Each
level of the tree contains a set of orthogonal spreading
codes. Codes at different levels of the tree are orthogonal, except
in the case where a path can be traced through a particular
code to the root of the tree. For example, in Figure 1, C_4(1) is
orthogonal to C_4(2), C_4(3), C_4(4), and C_4(2), but it is not or-
thogonal to either C_2(1) or C_1(1). The codes at each level of
the tree have a different spreading factor, allowing users to transmit
at different data rates.

\[
\begin{bmatrix}
C_N(1) \\
C_N(2) \\
\vdots \\
C_N(N-1) \\
C_N(N)
\end{bmatrix} =
\begin{bmatrix}
C_{N/2}(1) & C_{N/2}(1) \\
C_{N/2}(1) & C_{N/2}(1) \\
\vdots & \vdots \\
C_{N/2}(N/2) & C_{N/2}(N/2) \\
C_{N/2}(N/2) & C_{N/2}(N/2)
\end{bmatrix}
\]

(1)

IV. OVERVIEW OF OVSF CODE ASSIGNMENT
ALGORITHMS

Adachi, Sawahashi, and Okawa propose a tree-structured
method of generating orthogonal spreading codes with different
lengths [1]. The orthogonal properties of these codes support
different data rates in a CDMA system with only one spreading
code per user. The 3GPP WCDMA standard will utilize OVSF
codes for channel separation in the forward link [11]. Since the
orthogonal properties of OVSF codes limit which codes can be
simultaneously used, the efficient utilization of 3G wireless re-
sources will be significantly impacted by the code assignment
algorithm.

There are currently few published OVSF code assignment
algorithms. One factor contributing to the lack of published
algorithms is that OVSF codes are not widely used in exist-
ing CDMA systems. For example, the IS-95 CDMA standard
uses equal length spreading codes, rather than the newer OVSF
codes. The 3GPP WCDMA technical specifications require the
use of OVSF codes, but leave implementation details up to
equipment vendors [11]. The orthogonal properties of OVSF
codes present unique code assignment issues that do not exist in
CDMA systems with equal length spreading codes. Three re-
cently published algorithms deal with the issues of initial code
assignment [2], code blocking [3], and supporting different QoS
levels [4]. A brief summary of these algorithms follows.

Cheng and Lin present an assignment scheme for OVSF codes
that addresses the issue of initial code assignment [2]. They state
that it is advantageous to assign codes to low data rate users in a
manner that maximizes the available number of low SF, or high
data rate, codes. The authors define two criteria that can be used
to evaluate a code assignment scheme.

- Utilization is defined as the ratio of assigned bandwidth to
overall bandwidth. A code allocation scheme that preserves
more low SF codes has a better chance of providing higher utili-
ization.

- Complexity is defined as increasing with the number of codes
assigned to a single user.

Cheng and Lin assume that a user can be assigned multiple
OVSF codes to achieve different data rates. Their code assign-
ment algorithm assigns codes to as many users as possible, while
minimizing the number of codes per user. This algorithm ad-
dresses the problem of initial code assignment, but does not ad-
dress the problem of efficiently re-assigning codes after users
disconnect.

Minn and Siu propose a dynamic OVSF code assignment al-
gorithm that addresses the problem of code blocking [3]. Code
blocking occurs when the capacity exists to admit a user, but no
vacant orthogonal codes are available. Code blocking can oc-
cur when a number of users disconnect from the network. The
authors address this problem by reassigning existing users to
new codes in a manner that maximizes the available number of
low SF codes. Their algorithm addresses the problem of effi-
ciently re-assigning codes, but does not address supporting dif-
f erent types of traffic.

Fantacci and Nannicini present an algorithm that uses dy-
namic assignment of OVSF codes to support both real time and
non-real time traffic [4]. They consider real time CBR and VBR
traffic, which is represented by voice and video terminals. They
model non-real time traffic as both CBR and VBR. First, their
algorithm assigns codes to real time VBR and CBR users. Then,
non-real time users are assigned one of the remaining codes.
Non-real time users are required to either release their code,
or switch to a lower data rate when another real time user re-
quests access to the system. Fantacci and Nannicini’s algorithm
provides a method for non-real time traffic to utilize codes that
are not currently assigned to real time users. However, it does
not address the problem that bursty real time users will not effi-
ciently utilize their assigned bandwidth.
V. Dynamic OVSF Code Assignment Algorithm

We have developed a dynamic OVSF code assignment algorithm that efficiently shares bandwidth between bursty traffic sources with different QoS requirements. This algorithm addresses the issue that bursty traffic sources do not make efficient use of a dedicated code or channel assignment. High QoS traffic, i.e., traffic with demanding QoS level, requires a bandwidth reservation that can support its peak data rate. However, this bandwidth is not used when the bursty source is transmitting at less than its peak data rate. Our algorithm addresses the problem by dynamically changing the spreading code and bandwidth assigned to high QoS traffic. Best effort traffic is allowed to utilize an orthogonal spreading code when high QoS traffic is not transmitting at peak data rate. Our algorithm functions as follows.

1. Assign a high QoS traffic source a set of variable spreading factor codes consisting of a sub-section of the OVSF tree. The highest data rate code in the set must support the peak source data rate.
2. Begin transmitting QoS traffic on a code from the assigned set that supports the lowest data rate.
3. Allow best effort traffic to transmit on a code in the assigned set, which is orthogonal the code in use by the QoS traffic source.
4. If the delay for QoS traffic exceeds a threshold:
   - Switch QoS traffic to the parent code of the code currently in use to increase the data rate.
   - Block best effort traffic
   - Go to step 3.
5. If the channel utilization for the code currently used by QoS traffic falls below a threshold:
   - Switch QoS traffic to a child code of the code currently in use to reduce the data rate.
   - Block best effort traffic.
   - Go to step 3.

The operation of our dynamic code assignment algorithm can be illustrated with a two-level OVSF tree containing three spreading codes. For example, consider the highlighted section of Figure 1 containing the codes $C_2(1)$, $C_4(1)$, and $C_4(2)$. These three codes have spreading factors that support data rates of 30 Kbps, 15 Kbps, and 15 Kbps respectively. The set of codes can be used to reserve bandwidth for a high QoS traffic source with a peak data rate of 30 Kbps. High QoS traffic is initially assigned to the 15 Kbps channel corresponding to code $C_4(1)$. Likewise, best effort traffic is assigned to the 15 Kbps channel corresponding to code $C_4(2)$.

These two codes are orthogonal, both codes can be used simultaneously. If the delay on the high QoS 15 Kbps channel exceeds a threshold, then high QoS traffic is assigned to the 30 Kbps channel corresponding to code $C_2(1)$. Since code $C_4(2)$ is not orthogonal to code $C_2(1)$, best effort traffic is blocked while high QoS traffic is on the 30 Kbps channel. If the utilization on the 30 Kbps channel drops below a threshold, high QoS traffic is switched back to the 15 Kbps real time code $C_4(1)$, and best effort traffic is unblocked on code $C_4(2)$. Thus, the algorithm dynamically assigns the spreading codes to both limit high QoS packet delay, and allow best effort traffic to utilize available bandwidth.

VI. Simulation Results

We have developed a simulation model to test the performance of our algorithm using the commercial network simulation tool OPNET. The simulation models the wireless forward link between a base station and two mobile users. This number of mobile users is sufficient to test performance of the algorithm without incurring long simulation run times. The base station transmitter has three channels corresponding to the variable spreading factor codes $C_2(1)$, $C_4(1)$, and $C_4(2)$ in Figure 1. As discussed in Section V, code $C_2(1)$ supports a data rate of 30 Kbps while codes $C_4(1)$ and $C_4(2)$ each support 15 Kbps. These three spreading codes support a total bandwidth of 30 Kbps. The bandwidth can be allocated using a single 30 Kbps channel, or two 15 Kbps channels. These data rates represent the lowest data rates supported in WCDMA, and were selected to reduce simulation run times while testing the algorithm. Traffic is generated in the base station in the form of packets with a 32 bit address field, an 8 bit Type of Service (TOS) field, and 1000 bits of payload. The simulation is run under two scenarios with different traffic sources. The first scenario uses deterministic traffic sources to verify the correct operation of the algorithm. The second scenario uses bursty random traffic sources to evaluate the ability of the algorithm to support traffic with different QoS requirements.

A. Deterministic Traffic Results

The first simulation scenario utilizes deterministic traffic sources to simplify verification of the algorithm performance. The deterministic traffic is a combination of Constant Bit Rate (CBR) and on-off traffic sources, as shown in Figure 2. The BS transmits traffic to two mobile users identified as High QoS One, and Best Effort One. Table I summarizes the parameters of the traffic shown in Figure 2. The following scenario describes the desired operation of the dynamic code assignment algorithm under the deterministic traffic load.

When the simulation begins, the BS is transmitting CBR traffic to mobile High QoS One at 10 Kbps on a 15 Kbps channel. The BS is also initially transmitting CBR traffic to mobile Best Effort One at 10 Kbps on the other 15 Kbps channel. At time $t=5$ minutes, the base station begins transmitting an additional 10 Kbps of on-off traffic to mobile High QoS One on the 15 Kbps channel. The aggregate 20 Kbps of QoS traffic should flood the 15 Kbps channel, causing the algorithm to switch High QoS One to the 30 Kbps channel. At the same time, Best Effort One traffic should be blocked since the 15 Kbps code is not orthogonal to the 30 Kbps code. At time $t=10$ minutes, the on-off traffic to High QoS One stops and the 30 Kbps channel utilization should drop below 40 percent. This should trigger the algorithm to switch QoS traffic to the 15 Kbps channel, and unblock the best effort 15 Kbps channel. The queued traffic for mobile Best Effort One should saturate the 15 Kbps channel. At time...
TABLE I
DETERMINISTIC TRAFFIC PARAMETERS

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
<th>TOS</th>
<th>Traffic Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>High QoS One</td>
<td>QoS</td>
<td>CBR</td>
</tr>
<tr>
<td>B</td>
<td>High QoS One</td>
<td>QoS</td>
<td>On-off t=5-10</td>
</tr>
<tr>
<td>C</td>
<td>High QoS One</td>
<td>QoS</td>
<td>On-off t=15-20</td>
</tr>
<tr>
<td>D</td>
<td>Best Effort One</td>
<td>Best Effort</td>
<td>CBR</td>
</tr>
</tbody>
</table>

$t=15$ another burst of on-off traffic for mobile High QoS One should cause this cycle to repeat. Finally, the utilization of the best effort channel should drop to 66 percent when the queued packets for mobile Best Effort One have all been transmitted.

The correct operation of the code assignment algorithm can be shown by observing the transmitter channel utilization. Figure 3 shows the transmitter channel utilization for each of the three channels. The top two graphs present the utilization for the high QoS and best effort 15 Kbps channels respectively. The bottom graph shows the 30 Kbps channel utilization. Figure 3 demonstrates the correct operation of the algorithm. The BS is initially transmitting on both the high QoS and best effort 15 Kbps channels. At time $t=5$ minutes, the burst of traffic for High QoS One causes the algorithm to switch QoS traffic to the 30 Kbps channel. The best effort channel is blocked while the 30 Kbps channel is active. At time $t=10$ minutes, the on-off traffic for High QoS One stops causing the QoS traffic to switch back to the 15 Kbps channel, and unblocking the best effort channel. This cycle repeats for the second burst of on-off traffic to High QoS One at time $t=15$ minutes. Therefore, the algorithm is operating as expected.

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$B$. Random Traffic Results

The second simulation scenario uses random traffic sources to examine the algorithm’s effectiveness at supporting users with different QoS requirements. A Pareto distribution was used to randomly generate both high QoS traffic and best effort traffic. The heavy-tailed nature of the Pareto distribution produces traffic that is bursty in nature. Equation 2 gives the probability density function of the Pareto distribution, where $\alpha$ is the location parameter and $\beta$ is the shape parameter. The simulation was run with $\beta = 1.21$, which offers a good approximation for web traffic [12]. The value of $\alpha$ was varied to change the mean arrival time between packets. Two tests were conducted with the bursty random traffic sources. The first test measured the highest mean data rate for a single bursty source that the 30 Kbps channel could support without excessive queuing delay. We refer to this value as the soft channel capacity. The second test measured the ability of the algorithm to support best effort traffic when high QoS traffic was transmitting at less than the soft channel capacity.

$$f(x) = \frac{\beta \alpha^\beta}{x^{\beta+1}}, \quad \alpha \leq x \leq \infty$$

The allocation of bandwidth to a traffic source presents a trade-off between QoS guarantees and efficient resource utilization. A fixed capacity channel can only offer good end-to-end delay performance to a bursty traffic source if the mean data rate of the source is less than the channel capacity. The soft channel capacity of the 30 Kbps channel was measured by varying the location parameter $\alpha$ of the Pareto distribution and collecting statistics for the average end-to-end packet delay and average traffic received. Figure 4 shows the average end-to-end packet delay.
delay for values of \( \alpha \) between \( 11 \times 10^{-3} \) and \( 7 \times 10^{-3} \). The average end-to-end packet delay increases significantly when the value of \( \alpha \) changes from \( 10 \times 10^{-3} \) to \( 9 \times 10^{-3} \), exceeding an average value of one second. For the purposes of testing the simulation, this was selected as the threshold between acceptable and unacceptable delay performance. This value of end-to-end delay is sufficient to test the algorithm, as the actual threshold would be application dependent. Figure 5 shows the average traffic received by the mobile user for the same range of \( \alpha \) values as Figure 4. The mobile user receives an average of approximately 22 Kbps for \( \alpha = 10 \times 10^{-3} \). The soft channel capacity was therefore determined to be 22 Kbps.

The dynamic code assignment algorithm should make efficient use of the wireless channel without sacrificing QoS guarantees. In order to efficiently use the wireless channel, best effort traffic is allowed to utilize available bandwidth when high QoS traffic is transmitting at a mean data rate lower than the soft channel capacity. Ideally, the sum of high QoS traffic and best effort traffic should equal the soft channel capacity of 22 Kbps. The efficiency of the algorithm was tested by considering both high QoS and best effort traffic in the simulation. The best effort traffic used a constant value of \( \alpha = 15 \times 10^{-3} \). The high QoS traffic used values of \( \alpha \) between \( 25 \times 10^{-3} \) and \( 10 \times 10^{-3} \). Figure 6 shows the average value of all traffic received, both high QoS and best effort, for these simulation runs. The results show that the algorithm makes efficient use of the available bandwidth, with a net throughput of approximately 22 Kbps, for values of \( \alpha = 25 \times 10^{-3}, 20 \times 10^{-3}, 18 \times 10^{-3}, \text{and} \ 10 \times 10^{-3} \). However, the algorithm is less efficient for values of \( \alpha = 17 \times 10^{-3}, 16 \times 10^{-3}, \text{and} \ 15 \times 10^{-3} \). This can be explained by the fact that the channel only supports data rates of 15 Kbps and 30 Kbps. If the high QoS traffic mean data rate exceeds 15 Kbps, it will always transmit on the 30 Kbps channel blocking the best effort traffic. This is the case when the high QoS traffic is transmitting at the soft channel capacity of 22 Kbps using a value of \( \alpha = 10 \times 10^{-3} \). The average traffic received for values of \( \alpha \) between \( 17 \times 10^{-3} \) and \( 15 \times 10^{-3} \) are less than 22 Kbps because the best effort traffic is beginning to be blocked for a large percentage of the time, and most of the traffic received is high QoS traffic. Figure 7 gives a comparison between the average value of all traffic received and the average value of high QoS traffic received for a value of \( \alpha = 18 \times 10^{-3} \). The results show a mean data rate of the high QoS traffic is approximately 12 Kbps, below the threshold of 15 Kbps that will block best effort traffic. The mean data rate for all traffic is approximately 22 Kbps, illustrating that the algorithm allows best effort traffic to effectively utilize available bandwidth. Figure 8 shows the average end-to-end packet delay for both high QoS traffic and best effort traffic for a value of \( \alpha = 18 \times 10^{-3} \). The results demonstrate that the algorithm protects the QoS guarantees in terms of end-to-end delay for high QoS traffic while allowing best effort traffic to utilize available bandwidth. Therefore, the algorithm is performing as desired.

**VII. Conclusions and Future Work**

Emerging 3G wireless networks will offer improved data rates for applications such as web browsing, video teleconferencing, and other multimedia applications. Bandwidth for these applications will be reserved in 3GPP WCDMA networks through the use of OVSF codes. If bursty traffic sources are allocated sufficient bandwidth to guarantee low latency during peak transmission rates, they will make inefficient use of this bandwidth when transmitting at lower data rates. In this paper we have presented a dynamic OVSF code assignment algorithm, which makes efficient use of wireless resources for bursty traffic sources with
different QoS requirements. This algorithm improves upon previously published OVSF code assignment algorithms [2][3][4] by exploiting the fact that data traffic is bursty in nature. This is accomplished by allowing best effort traffic to transmit when high QoS traffic is not fully utilizing its reserved bandwidth. Our simulation results verify that the algorithm functions as desired. The QoS guarantees for high QoS traffic are protected, and best effort traffic is able to utilize available bandwidth. Our future research efforts will focus on improving the dynamic code assignment algorithm by increasing the data rates supported, and examining the effects of statistically multiplexing high QoS bursty traffic sources on a shared downlink channel.

REFERENCES


