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Conference Paper · July 2004
DOI: 10.1109/INCC.2004.1366580 · Source: IEEE Xplore

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A High-Capacity Scheduling Algorithm for Systems Employing Embedded Modulation

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Abstract – This paper proposes a simple scheduling algorithm based on adaptive embedded modulation (EM) for the downlink in urban wireless networks. Embedded modulation allows multiple users to share a single downlink channel simultaneously. The proposed EM scheduling algorithm embeds the user which has the largest carrier-to-interference ratio (C/I) with each of the lower C/I users in turn. Simulation results show that the EM scheduler, employing adaptive coded modulation, can improve the average throughput of a given downlink by up to 33% over a round robin scheduler, while still maintaining acceptable fairness amongst the system users.

Index Terms – Embedded modulation, adaptive coded modulation, multiuser scheduling, system fairness.

I. INTRODUCTION

Given the hostile fading and multipath characteristics of mobile communication channels, mobile communication systems require sophisticated signal processing techniques to improve the link performance. In addition, the radio spectrum available for wireless services is extremely scarce, while the demand for such services is growing at a rapid pace. Spectral efficiency is therefore of considerable importance in the design of future wireless data communication systems.

In this paper we propose a new technique for improving spectral efficiency on the downlink in urban wireless networks, where the transmitted signal is corrupted by signal path loss, Ricean fading, lognormal shadowing, AWGN, and interference from neighbouring cells. This technique can be viewed as an extension of adaptive coded modulation (ACM), wherein the base transceiver station (BTS) adapts the code rate and modulation scheme in response to estimates of the downlink carrier-to-interference ratio (C/I) provided by the mobile receiver. The proposed technique employs embedded modulation (EM), wherein the symbols destined for two or more separate users are “embedded” in a single ACM signal constellation at the BTS and transmitted simultaneously. In the course of this research, the theoretical idea behind embedding users has been transformed into a practical scheduling algorithm. This algorithm embeds the user which has the largest C/I with each of the lower C/I users in turn. Multiuser embedded modulation realizes higher average throughput per channel use than that achieved by single-user ACM.

The organization of this paper is as follows. Section II talks about the advantage of using ACM as a link adaptation technique. Section III briefly explains the concept of multiuser embedding. Section IV describes the objectives in scheduling, followed by a detailed description of the proposed EM scheduler. The system model and computer simulation results are presented in Section V.

II. ADAPTIVE CODING AND MODULATION

To compensate for the time-varying nature of the channel, variable-rate ACM has proven to perform with significant gains in channel throughput relative to fixed-rate coding and modulation. Many researchers have contributed to the development of ACM for single-user frequency-flat slow fading multipath channels [1, 2, and the references therein]. In an ACM system, the receiver estimates the current channel C/I for the link and conveys this information to the transmitter through a low capacity feedback link. Based on this information, the transmitter selects the appropriate code rate and modulation scheme that will maximize the throughput while maintaining a fixed average transmit power. This results in variable throughput in terms of the number of information bits transmitted per channel use (bpcu). The average value of this throughput is used as the metric for evaluating system performance in this paper.

For ease of implementation, the transmitter is limited to selecting the code rate and modulation scheme from a finite set of ACM operating modes, such as those listed in Table I, for example. These ACM modes, which are taken from the HiperLAN system, are used for the simulation results presented in Section V [3]. The variable code rates are achieved by puncturing the 64-state convolutional code with generator (133, 171)8. Bit interleaved coded modulation (BICM) is used for transmission. Although each ACM mode has its own nominal throughput, as shown in Table I, due to packet errors
and consequent retransmissions the link actually operates at an effective throughput that is less than the nominal one. Figure 1 shows the effective throughput as a function of C/I for the ACM modes listed in Table I, assuming a packet size of 200 bits. For a given C/I, the transmitter selects the ACM mode that gives the highest effective throughput.

### III. Embedded Modulation

Embedded modulation allows two (or possibly more) mobile users to share a single downlink channel simultaneously [4]. By means of embedded modulation, a new signal constellation is created in which information meant for two different users is superimposed in the same channel symbol. To demonstrate this, a $4 \times 4$ EM constellation is shown in Figure 2. The 16 points of the embedded constellation are grouped into four “clouds”, each containing four signal points. The minimum separation of the points within a cloud is $d_1$, and the minimum separation between clouds is $d_2$, such that $d_2 \gg d_1$; [4, 5]. The signal labelling is done in such a fashion that the first two bits specify the cloud, and the last two bits specify the point within the cloud. Observe that a user with a low C/I may only be able to determine the cloud containing the transmitted point, but not the actual point within the cloud. Hence it could reliably detect the first two bits, but not the last two. A user with a high C/I, on the other hand, could determine all four bits, although would only be interested in the last two. The use of EM in this case therefore involves pairing two users, one with a high C/I and one with a low C/I. The control channel on the forward link would inform each user beforehand of its prospective bit positions within the EM symbol.

This general idea is easily extended to different EM constellations, such as $2 \times 4$ EM, where only one bit is sent to the low C/I user and two bits are sent to the high C/I user. Different coding rates can also be applied to the data for the different users. It is also important to note that the intra- and inter-cloud separation ($d_1$ and $d_2$ respectively) are constrained to ensure fixed average transmit power. This implies that the effective throughput to each individual user may be less than what could be attained had the transmitter served only one user, using the best possible single-user ACM mode. Nonetheless, the combined throughput to both embedded users actually exceeds that of single-user ACM.

### IV. Embedded Modulation Scheduling Scheme

#### A. Objectives in Scheduling

The objectives of a scheduler are to maximize the aggregate channel throughput and to guarantee a degree of throughput fairness to all the users. Since these objectives do not necessarily compliment each other, there is a tradeoff involved between the two. To understand this better we take a look at two existing scheduling algorithms. One is the max-C/I scheme, in which the BTS only serves the user with the highest C/I [6]. This system tends to mostly use the highest possible ACM mode for transmission, so the average throughput is very high. On the other hand, users experiencing poor C/I...
are seldom if ever served, thus this scheme is very unfair and would starve some users in real situations. Another scheduling scheme is based on the round robin (RR) algorithm in which the BTS serves all users in turn. Although the BTS resources are allocated fairly amongst users, less efficient ACM modes must be employed to serve the users with poor C/I's. This results in a reduced system throughput.

In a system using ACM, different users may receive different throughput due to their different C/I's. Throughput fairness is defined as the disparity in per user throughput. Although there are many ways to describe this disparity, in this paper we use the fairness criteria proposed by Qualcomm and Motorola in the 3GPP2 standards forum for 1xEV-DV system evaluation [7, 8, 9]. This fairness criteria is defined in Table II. The fairness is evaluated by determining the cumulative distribution function (CDF) of the user throughput normalized to the average system throughput for all the users. A system is classified as fair if the user CDF lies to the right of the curve given by the three points in Table II.

### B. Proposed EM Scheduler

Taking perspective of the scheduling tradeoff, our paper proposes an embedded modulation scheduling scheme. The performance of this scheme lies in between that of the max-C/I and the RR algorithms such that it is more fair than the former and produces a higher average throughput than the latter.

This scheme works with a set of N simultaneous users served in N consecutive transmission slots. The users are sorted in an ascending order of C/I's, such that user 1 has the lowest C/I, and user N has the highest. In time slot n ∈ {1, 2, ..., N - 1}, information for the user having the highest C/I in the set (i.e., user N) is embedded with the information for user n. In the last (Nth) time slot, only the max C/I (Nth) user is served, using single-user ACM. This algorithm has the effect of increasing the throughput in each embedded channel use over that of single-user ACM. To control fairness in this scheme, there is a restriction placed on the minimum throughput going to the low C/I user. This restriction is defined in terms of a variable β, such that the minimum throughput delivered to a low C/I user cannot be lower than β percent of the effective throughput it would have received had single-user ACM been used instead.

By introducing the fairness control parameter β in this way, the scheduler can control the fairness of the scheme. If β is set to 100% then EM will not be used, and the scheduler will work as a RR scheduler. If β = 0%, then all of the throughput will be delivered to the max-C/I user alone.

### V. System Simulation

#### A. System Model

The transmitted signal is degraded by signal path loss, Ricean fading, lognormal shadowing, AWGN, and interference from neighbouring cells. The system parameter values, which correspond to the 1xEV-DV system [9], are listed in Table III. The cumulative distribution function of the users' C/I based on these parameters is plotted in Figure 3. We consider a slowly varying flat-fading channel changing at a rate much slower than the symbol data rate, so the channel remains roughly constant over hundreds of symbols.

#### B. Simulation Results

The results presented in this paper have been obtained by averaging over 100,000 runs of N transmit time slots each, where N is also the number of users. It is assumed that all the users have some data to send at all times, i.e., they have full buffers during the simulation run. Figure 4 shows the average throughput obtained by the EM scheme as a function of the number of system users, for various values of β. The throughput values of the max-C/I and RR schemes are also plotted. As can be seen, decreasing β leads to improved throughput. With the appropriate choice of β it is possible to attain any desired throughput between that of the max-C/I and

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**TABLE II - FAIRNESS CRITERIA**

<table>
<thead>
<tr>
<th>Normalized Throughput</th>
<th>User CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**TABLE III - FORWARD LINK SYSTEM PARAMETERS [9]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells (3 sectored)</td>
<td>19 hexagonal cells</td>
</tr>
<tr>
<td>Antenna Horizontal Pattern</td>
<td>70° (-3 dB beamwidth) with 20 dB max attenuation</td>
</tr>
<tr>
<td>Propagation Model</td>
<td>3.15 + 35log_{10}(d) dB d in metres</td>
</tr>
<tr>
<td>BTS Site-to-Site Distance</td>
<td>2.5 km</td>
</tr>
<tr>
<td>Log-Normal Shadowing</td>
<td>Standard Deviation = 8.9 dB</td>
</tr>
<tr>
<td>Mobile Noise Figure</td>
<td>10.0 dB</td>
</tr>
<tr>
<td>Additive Thermal Noise Density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>BTS: 15 dB; MS: -1 dB</td>
</tr>
<tr>
<td>Ricean Fading Model</td>
<td>K = 3</td>
</tr>
<tr>
<td>BTS Fixed Transmit Power</td>
<td>43 dBm; 20 W</td>
</tr>
<tr>
<td>Minimum Acceptable C/I</td>
<td>4 dB</td>
</tr>
<tr>
<td>Maximum Achievable C/I</td>
<td>24 dB</td>
</tr>
<tr>
<td>Transmission Bandwidth</td>
<td>1.25 MHz</td>
</tr>
</tbody>
</table>
the RR schemes. However, making $\beta$ too small will lead to a violation of the fairness criteria. For any given number of users there is a specific minimum allowable $\beta$ value that will provide the minimum required fairness. Figure 4 also shows the throughput achieved when this minimum fair value of $\beta$ is used. It can be seen that the EM scheme is able to deliver a fair average throughput of 2.9 bpcu for a system with 80 users, representing a gain of 33.0% over the RR scheme.

To further explore the tradeoff between throughput maximization and system fairness, Figure 5 shows the CDF of the normalized throughput, for a system with 40 users. This figure shows the fraction of users receiving a throughput of less than the corresponding value along the abscissa. The abscissa represents user throughput normalized to the average value so that any evaluation is independent of the absolute throughput numbers. The CDF for a fair system must fall below or to the right of the indicated fairness criteria. Also shown in Figure 5 are the percentage gains in throughput of each of the schemes over the RR scheme.

The RR curve demonstrates high throughput fairness amongst concurrent users, whereas the max-C/I curve tells us that 4% of the users are served with the maximum possible throughput and the remaining 96% are not served at all. The positions of the various EM scheme curves show the effect of varying $\beta$ in order to control the fairness. Through these curves we can closely observe the fairness provided by the different schemes. The EM curve with $\beta = 60\%$ slightly violates the fairness criteria, but with $\beta$ set to 65%, the resulting curve lies just to the right of the fairness criteria hence providing a fair throughput to the poor C/I users. Hence for 40 users, the minimum fair value of $\beta$ is about 65%, and with this value of $\beta$ the EM scheme gives a gain of 31.0% over the throughput for the RR scheme. Increasing $\beta$ to 75% would shift the fairness curve further right such that the fairness would improve but the average throughput would decrease.

VI. CONCLUSIONS

Using embedded modulation with an appropriate scheduling algorithm provides a flexible means for increasing the aggregate channel throughput while guaranteeing a degree of throughput fairness to all the users. Always embedding the max C/I user with the lower C/I users is a simple method for acquiring higher throughput as well as delivering an acceptably fair number of bits to the lower C/I users. The lower C/I users are not as disadvantaged as they would be in a max-C/I scheme, and the average channel throughput increases over that of RR. Hence the EM scheme provides a balanced and fair alternative to these two existing scheduling algorithms.
REFERENCES