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Dynamic Code Assignment and Spreading Gain Adaptation in Synchronous CDMA Wireless Networks

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Abstract— **DS-CDMA has been recognized as the major candidate for providing high and variable data rates in third generation wireless networks, where multi-code structures and different spreading gains will be employed. In this paper, we address the problem of assignment of variable spreading gain deterministic codes to a set of users, with the objective to maximize down-link system throughput. We propose an algorithm to allocate codes to users with different minimum rate requirements, based on code cross-correlation properties and spreading gains. Our algorithm first constructs an admissible set of codes by using criteria which are based on induced interference to the system and code rates. These codes are then appropriately assigned to users, so that user rate requirements are satisfied. Comparative numerical results for different performance measures of these criteria are also provided.**

I. Introduction

The last frontier in wireless communication networks is the provisioning of high and variable data rates to heterogeneous users for supporting a mixture of diverse applications, such as voice, video and data. Next generation applications will mostly carry bursty traffic, which must be handled differently than existing voice traffic, where the objective is to maintain constant link quality. Due to the increasing demand for limited network resources and the trend towards variable, higher data rates, sophisticated resource utilization and assignment are indispensable.

The predominant third generation physical layer technique for delivering wireless access to users is Direct-Sequence Code Division Multiple Access (DS-CDMA). In DS-CDMA, user symbols are modulated by a high-rate chip sequence, the spreading code or signature sequence. The number of chips per symbol is called spreading gain. Many users can transmit in the same wide frequency band, if a unique code is assigned to each user. Second generation CDMA systems are based on the IS-95 standard. Third generation CDMA technology encompasses the Wide-band CDMA (W-CDMA) and cdma2000 standards, where a wide range of higher data rates is achieved with multi-code structures and different spreading gain per code [1].

A fundamental goal in DS-CDMA is to satisfy QoS requirements for users. These are usually expressed in terms of achievable data rate, signal-to-interference and noise ratio (SINR) or bit error rate (BER). Depending on user requirements and resource availability, a user can be assigned multiple codes, each of different spreading gain, in order to satisfy QoS requirements. The performance of a DS-CDMA system is significantly affected by the design and assignment of signature sequences to users. Although orthogonal signatures eliminate inter-user interference, code orthogonality may vanish at the receiver, due to lack of synchronization and multi-path effects. Further, low spreading gain codes provide high rates, but they have low diversity gain against channel impairments and do not efficiently suppress other user interference.

Two general approaches can be identified in the literature. The first one assumes deterministic signature sequences and focuses on their design, so as to maximize capacity of the DS-CDMA channel. The optimal set of Welch bound equality (WBE) signature sequences was first identified in [2], in the sense that the total squared cross-correlation (TSC) of the signature sequences is minimized and Welch bound is achieved. WBE sequences have been shown to maximize sum capacity of the CDMA channel for equal received powers [3]. In [4] and [5], the authors present a technique for signature design and power allocation, so that up-link and down-link channel sum capacity are maximized. In [6], an iterative technique for distributed signature update is proposed that converges to the minimum TSC signature sequence set.

The second approach deals with codes that are randomly generated and assigned to users. Then, code cross-correlation terms are eliminated from SINR expressions and SINR depends on received powers and spreading gain. Under this assumption, the main trend in literature is to adapt spreading gains and powers in order to maximize system throughput. In [7], spreading gain adaptation policies for minimum probability of packet retransmission are considered. Power control for fixed spreading gain multi-code DS-CDMA and variable spreading gain single-code DS-CDMA is studied in [8]. Finally, spreading gain and power control for maximum system throughput are studied in [9], where throughput is expressed as a function of achievable rates and the amount of packet retransmissions.

The main feature of these approaches is that they focus on physical layer aspects of the problem, such as signature design and spreading gain or transmission power adaptation. In addition, spreading gain is assumed constant in deterministic signature studies and is adaptable only in random signature cases. In this work, we investigate the problem of deterministic assignment of variable spreading gain codes to a set of users with different rate requirements, with the objective to enhance system throughput. We follow a cross-layer approach, in the sense that we consider the impact of physical layer code properties on MAC layer code assignment.

The paper is organized as follows. In section II, we provide the model used in our approach. In section III, we describe the problem and present the proposed algorithm for deterministic assignment of variable spreading gain codes to users. Numerical results are illustrated in section IV. Finally section V concludes our study.

II. System Model

We consider the down-link of a single-cell synchronous DS-CDMA system with M binary antipodal codes $\{\mathbf{s}_i\}_{i=1}^{M}$ available at the base station. Each code can have different spreading gain N_i and the maximum spreading gain is N_{max}. Let $\mathbf{c}_i$ denote the normalized version of $\mathbf{s}_i$, so that $\mathbf{c}_i \in \left\{\pm\frac{1}{\sqrt{N_i}}\right\}^{N_i}$, for $i = 1,\ldots M$ and $\mathbf{c}_i^T\mathbf{c}_i = 1$, where T denotes the transpose operation. A code $\mathbf{c}_i$ of spreading gain N_i is associated with rate $r(\mathbf{c}_i) = r(\mathbf{s}_i) = 1/(T_c N_i)$, where T_c is the (common for all codes) chip duration. Spreading gains are assumed to satisfy the following condition, which facilitates framing at the receiver: any spreading gain is the common multiple of all lower value spreading gains. A frame structure of duration T_f is thus imposed by N_{max}, so that $T_f = N_{max}T_c$.

There exist K users in the cell and user k is characterized by channel gain h_k. Antipodal BPSK modulation is employed for all users, so that $b_k \in \{-1, 1\}$ for each information symbol b_k of user k. Each user k has a minimum rate requirement $r_{min,k}$ (in bits/sec), which must be satisfied by the assignment algorithm. In general, multiple codes can be assigned to a user, but each code can be assigned to at most one user. The set of all M codes is $\mathcal{C}$ and the set of codes assigned to user k is $\mathcal{C}_k$. Finally, the cardinality of a set $\mathcal{X}$ is denoted by $|\mathcal{X}|$.

Assume for a moment that M codes of equal spreading gain N are used. The received signal at the input of the receiver of user k in a symbol interval is,

$$\mathbf{y}_k = \sum_{n=1}^{K}\sum_{\mathbf{c}_i\in\mathcal{C}_n} h_k b_n^i \mathbf{c}_i + \mathbf{n}, \quad (1)$$

where b_n^i is the information symbol of user n, which is transmitted with code $\mathbf{c}_i \in \mathcal{C}_n$ and $\mathbf{n}$ is zero mean white Gaussian noise with variance σ^2.

The receiver of user k consists of a bank of $|\mathcal{C}_k|$ matched filters, each of which is matched to code $\mathbf{c}_i \in \mathcal{C}_k$. For the symbol-synchronous case, useful signal and interference are received synchronously at each matched filter. The signal at the output of the matched filter corresponding to code $\mathbf{c}_i \in \mathcal{C}_k$ is $y_k^i = \mathbf{c}_i^T\mathbf{y}_k$, which can be expanded as,

$$y_k^i = h_k\mathbf{c}_i^T\left(\sum_{\substack{n=1\\n\neq k}}^{K}\sum_{\mathbf{c}_j\in\mathcal{C}_n} b_n^j\mathbf{c}_j + \sum_{\substack{\mathbf{c}_j\in\mathcal{C}_k\\ j\neq i}} b_k^j\mathbf{c}_j + b_k^i\mathbf{c}_i + n\right), \quad (2)$$

where the first two terms capture the effect of interference on code $\mathbf{c}_i$ from other users' codes and other codes of user k, while the third term leads to the useful signal. Since total induced interference to code $\mathbf{c}_i$ is due to all other codes, irrespective of users, y_k^i can be written as,

$$y_k^i = h_k\left(\sum_{\substack{\mathbf{c}_j\in\mathcal{C}\\ j\neq i}} b_j\rho_{ij} + b_k^i\rho_{ii}\right), \quad (3)$$

where b_j denotes a user symbol carried by code $\mathbf{c}_j \neq \mathbf{c}_i$ and ρ_{ij} is the cross-correlation between codes $\mathbf{c}_i$ and $\mathbf{c}_j$, defined as $\rho_{ij} = \mathbf{c}_i^T\mathbf{c}_j$, with $\rho_{ii} = 1$. Then, the SINR at the output of the matched filter corresponding to $\mathbf{c}_i \in \mathcal{C}_k$ is,

$$SINR(\mathbf{c}_i) = \frac{1}{\sum_{j=1,j\neq i}^{M}\rho_{ij}^2 + \sigma^2}. \quad (4)$$

Consider now codes $\mathbf{c}_i$ and $\mathbf{c}_j$ with spreading gains N_i and N_j. Let $\tilde{\rho}_{ij} = \mathbf{s}_i^T\mathbf{s}_j$ be the cross-correlation of the unnormalized codes $\mathbf{s}_i$ and $\mathbf{s}_j$, so that $\rho_{ij} = \tilde{\rho}_{ij}/\sqrt{N_iN_j}$. Equation (4) can be written equivalently as[1],

$$SINR(\mathbf{s}_i) = \frac{N_i}{\sum_{j=1,j\neq i}^{M}\frac{\tilde{\rho}_{ij}^2}{N_j} + \sigma^2}. \quad (5)$$

We now need to define $\tilde{\rho}_{ij}^2$ for $N_i \neq N_j$. We first make the following notational remarks for a code $\mathbf{s}_i = [s_{i,1},\ldots,s_{i,N_i}]^T$ of spreading gain N_i:

- $\mathbf{s}_i^{(k)}$: a new code, formed by concatenating code $\mathbf{s}_i$ to itself $k-1$ times. E.g. $\mathbf{s}_i^{(2)} = [\mathbf{s}_i\,\mathbf{s}_i]^T$, $\mathbf{s}_i^{(3)} = [\mathbf{s}_i\,\mathbf{s}_i\,\mathbf{s}_i]^T$, etc.
- $\mathbf{s}_i^{(\ell,L)}$: the ℓ-th L-length subsequence of $\mathbf{s}_i$, such that $\mathbf{s}_i^{(\ell,L)} = [s_{i,[1+(\ell-1)L]},\ldots,s_{i,(\ell L)}]^T$, for $\ell = 1,\ldots,N_i/L$. E.g., if $\mathbf{s}_1 = [+1+1\text{-}1\text{-}1]^T$ and $L = 2$, then $\mathbf{s}_1^{(1,2)} = [+1+1]^T$ and $\mathbf{s}_1^{(2,2)} = [\text{-}1\ \text{-}1]^T$.

Consider the following example of three codes $\mathbf{s}_1$, $\mathbf{s}_2$ and $\mathbf{s}_3$ with spreading gains 4, 8 and 16, where $\mathbf{s}_1 = [+1\text{-}1+1\text{-}1]^T$, $\mathbf{s}_2 = [+1+1+1\text{-}1\text{-}1\text{-}1+1+1]^T$, and $\mathbf{s}_3 = [+1+1\text{-}1\text{-}1\ +1+1\text{-}1\text{-}1+1+1\text{-}1\text{-}1+1+1\text{-}1\text{-}1]^T$ (Figure 1). Consider squared cross-correlation $\tilde{\rho}_{21}^2$ between $\mathbf{s}_2$ and $\mathbf{s}_1$. The matched filter for the longer code $\mathbf{s}_2$ at T_{s_2} sees two *replicas* of the shorter code $\mathbf{s}_1$ in a symbol period T_{s_2}. Then, $\tilde{\rho}_{21}$ becomes the inner product of $\mathbf{s}_2$ with the concatenated version of $\mathbf{s}_1$. Now consider squared cross-correlation $\tilde{\rho}_{23}^2$ between $\mathbf{s}_2$ and $\mathbf{s}_3$. The matched filter for the shorter code $\mathbf{s}_2$ at T_{s_2} sees two *sub-sequences* of the longer code $\mathbf{s}_3$, each of length 8, and the SINR requirement for $\mathbf{s}_2$ should be satisfied for all such sub-sequences. It is thus meaningful to consider worst case SINR, which occurs when the squared cross-correlation between $\mathbf{s}_2$ and one of the two sub-sequences is maximum. The formal definition of squared cross-correlation of codes $\mathbf{s}_i$ and $\mathbf{s}_j$ with spreading gain ratio $R = N_j/N_i$ is,

$$\tilde{\rho}_{ij}^2 = \begin{cases}\left(\mathbf{s}_i^T\mathbf{s}_j^{(1/R)}\right)^2, & \text{if } N_i > N_j\\ \max\limits_{k=1,\ldots,R}\left(\mathbf{s}_i^{(k,R)^T}\mathbf{s}_j\right)^2, & \text{if } N_i < N_j\end{cases} \quad (6)$$

[1]Spreading gains also affect noise power; it will be assumed that interference is the major limitation, rather than noise power.

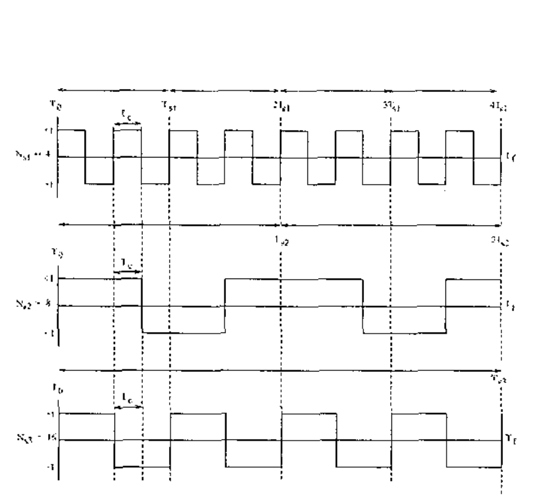

Fig. 1. Illustrative example for the cross-correlation for codes of different spreading gains.

A certain BER requirement ϵ for all assigned codes of a user must be satisfied. The minimum required SINR per code to maintain $BER \leq \epsilon$ for BPSK modulation is denoted by SINR threshold γ.

III. Deterministic Code Assignment with Spreading Gain adaptation

A. Problem Statement

When a lower spreading gain code is used by a user, symbol duration becomes shorter and data rate increases. If lower spreading gain codes are assigned to a user, the user needs fewer codes to reach rate requirements. Thus, more users are accommodated in the system for a given set of codes and capacity is increased. However, a lower spreading gain code has lower SINR and induces higher interference to other codes, as (5) suggests. Thus, lower spreading gain codes do not favor use of many codes with acceptable SINR. From that point of view, they do not contribute to throughput enhancement. On the other hand, a higher spreading gain code has lower rate. Since a user with higher spreading gain codes needs more codes to satisfy rate requirements, system capacity is decreased. However, higher spreading gain codes allow more codes to be used, due to higher SINRs and less induced interference to other codes.

Clearly, there exists a tradeoff between spreading gains and number of utilized codes, with respect to achievable throughput. The question that arises is which codes of different spreading gains must be assigned to users, so as to achieve high throughput and satisfy user rate requirements. Ideally, we would like to use as many codes of low spreading gain as possible. This could be achieved in the case of nearly orthogonal codes due to small inter-code interference. However, if code cross-correlations and spreading gains are such that the amount of interference is significant, then only a subset of codes with certain spreading gains may be admissible in the system. User rate requirements are achievable either by more high spreading gain codes or by fewer low spreading gain codes.

An assignment of M codes to users is specified by vector $(\alpha_1, \alpha_2, \ldots, \alpha_M)$, where $\alpha_i \in \{1, \ldots, K\} \cup \{0\}$ denotes the user to which code $\mathbf{s}_i$ is assigned. Code assignment involves (i) code admission in the system and (ii) code allocation to users. If $\alpha_i = 0$, $\mathbf{s}_i$ is not admitted in the system. Let $\mathcal{A}$ denote the set of all possible code assignments. We can index assignments as $d = 1, 2, \ldots$, and map assignment index d to vector $[\alpha_1(d), \alpha_2(d), \ldots, \alpha_M(d)]$. The set of codes assigned to user k with assignment d is $\mathcal{C}_k(d)$. Then our code assignment problem for maximum system throughput can be formally stated as follows:

$$\max_{d \in \mathcal{A}} \sum_{\substack{i=1 \\ \alpha_i(d) \neq 0}}^{M} r(\mathbf{s}_i), \tag{7}$$

subject to a minimum SINR requirement per code,

$$SINR(\mathbf{s}_i) \geq \gamma, \text{ for } i = 1, \ldots, M, \text{ s.t. } \alpha_i(d) \neq 0, \tag{8}$$

and a minimum rate requirement constraint for each user,

$$\sum_{\mathbf{s}_i \in \mathcal{C}_j(d)} r(\mathbf{s}_i) \geq r_{min,j}, \text{ for } j = 1, \ldots, K. \tag{9}$$

Observe that SINRs of admitted codes depend only on the set of admitted codes itself through their cross-correlations and are independent of code allocation to users. A set of admitted codes, in which all codes satisfy constraint (8) is called *admissible*. An allocation of an admissible code set to users, such that constraint (9) is satisfied, is called a *feasible* allocation. Among all feasible allocations, we want to identify the one that maximizes system throughput. However, enumeration of all admissible code sets is of exponential complexity, and feasibility of code allocations cannot be easily verified, as will be shown in the sequel. Hence, it is desirable to design a heuristic algorithm for code admission and code assignment to users.

B. Proposed approach

Based on our previous observation, the code assignment procedure consists of two phases: (i) determination of admissible set of codes and (ii) code allocation to users.

B.1 Code admission

In code admission, user rate requirements are not considered. The key idea is to admit as many codes as possible in the system, while enabling codes to have high rates, i.e, have low spreading gains. The criterion under which codes are admitted is crucial. Interference among codes affects code set admissibility and must be minimized during code admission in order to facilitate more future code admissions with acceptable code SINR. However, this goal contradicts admission of high rate codes. We thus propose different admission criteria that capture the impact of these factors. In the sequel, we assume that the major limitation is interference rather than noise and that SINR is approximated by SIR. Let $\mathcal{S}_0$ be the set of codes that have already been admitted. The next code $\mathbf{s}_i$ must be selected.

Criterion 1: Minimum SINR decrease with spreading gain consideration

For each code $\mathbf{s}_i \in \mathcal{C} \setminus \mathcal{S}_0$, we define an admission factor when $\mathbf{s}_i$ is tentatively admitted. A code should be admitted if it incurs low interference to other admitted codes and thus leads to minimum decrease of their SIRs. Let $SIR_j^{(-)}$, $SIR_j^{(i,+)}$ denote the SIR of code $\mathbf{s}_j \in \mathcal{S}_0$ before and after admission of $\mathbf{s}_i$. The SIR decrease of $\mathbf{s}_j$ due to $\mathbf{s}_i$ is $\Delta SIR_j^i = SIR_j^{(-)} - SIR_j^{(i,+)}$ and

$$\Delta SIR_j^i = \frac{N_j}{\sum_{\mathbf{s}_k \in \mathcal{S}_0 : k \neq j} \frac{\tilde{\rho}_{jk}^2}{N_k}} - \frac{N_j}{\sum_{\mathbf{s}_k \in \mathcal{S}_0 : k \neq j} \frac{\tilde{\rho}_{jk}^2}{N_k} + \frac{\tilde{\rho}_{ji}^2}{N_i}} . \quad (10)$$

An admitted code $\mathbf{s}_i$ should also receive low interference from other admitted codes, so that its SIR is high. In addition, low spreading gain codes should be given priority for admission, due to high code rates. To capture all these objectives, for each code $\mathbf{s}_i \in \mathcal{C} \setminus \mathcal{S}_0$ with spreading gain N_i, we define Admission Factor (AF) A_i as,

$$A_i = N_i \cdot \frac{\sum_{\mathbf{s}_j \in \mathcal{S}_0 : j \neq i} \Delta SIR_j^i}{SIR_i}. \quad (11)$$

Thus, among codes that cause or receive the same amount of interference, the one with higher rate (lower spreading gain) is preferable. Moreover, among codes of same rate, the one with the smallest amount of received or induced interference is admitted. The code with the minimum AF in $\mathcal{C} \setminus \mathcal{S}_0$ is always selected for admission.

Criterion 2: Minimum TSC of admitted codes

TSC of codes is considered as a reliable measure for intercode interference[2],[6]. For each code $\mathbf{s}_i \in \mathcal{C} \setminus \mathcal{S}_0$, we define

$$TSC_i = \sum_{\mathbf{s}_j \in \mathcal{S}_0} \frac{\tilde{\rho}_{ij}^2}{N_j} + \sum_{\mathbf{s}_j \in \mathcal{S}_0} \frac{\tilde{\rho}_{ji}^2}{N_i}, \quad (12)$$

where the first term is a measure of the interference that $\mathbf{s}_i$ receives from already admitted codes and the second term captures induced interference from $\mathbf{s}_i$ to other admitted codes. Codes with minimum TSC_i are sequentially admitted in the system. This criterion is based only on an interference measure and not on code rates.

Criterion 3: SIR Balancing for admitted codes

The objective of this criterion is to admit code $\mathbf{s}_i$, such that SIRs of admitted codes are as balanced as possible. For each code $\mathbf{s}_i \in \mathcal{C} \setminus \mathcal{S}_0$, we define factor

$$W_i = \max \left\{ \max_{\mathbf{s}_j \in \mathcal{S}_0} \frac{1}{SIR_j^{(i,+)}} , \frac{1}{SIR_i} \right\}, \quad (13)$$

where the quantity in brackets is the worst case code SIR after $\mathbf{s}_i$ is admitted. The algorithm selects code $\mathbf{s}_i$, such that the minimum SIR among admitted codes is maximized, that is $\mathbf{s}_i$ with minimum W_i. By maximizing the minimum SIR among admitted codes, we encourage admission of more codes in the system.

Depending on the employed criterion, the algorithm selects code $\mathbf{s}_i$ with minimum A_i, TSC_i or W_i, so that all admitted codes satisfy the SIR requirement. After each code admission, set $\mathcal{S}_0$ is updated. The procedure terminates when no more codes can be admitted.

B.2 Code allocation to users

After determining the final set of admissible codes $\mathcal{S}$ under an admission criterion, a feasible allocation of codes to users must be found, so that user rate requirements are satisfied. If $\sum_{\mathbf{s}_i \in \mathcal{S}} r(\mathbf{s}_i) < \sum_{j=1}^{K} r_{min,j}$, a feasible code allocation for that admission criterion does not exist. On the other hand, if $\sum_{\mathbf{s}_i \in \mathcal{S}} r(\mathbf{s}_i) \geq \sum_{j=1}^{K} r_{min,j}$, the problem of finding a feasible allocation of codes to users is not of polynomial complexity. To see this, let code $\mathbf{s}_i \in \mathcal{S}$ with spreading gain N_i be an item of size $r(\mathbf{s}_i)$. Each user j with rate requirements r_{min}, j can be perceived as a bin of that size. Then, the code allocation problem to K users is equivalent to the Bin Packing problem. "Given $|\mathcal{S}|$ items, each of size $r(\mathbf{s}_i)$ and integer K, can we pack the items into K bins?", which is known to be NP-Complete [10].

Several heuristics can be found for code allocation to users. Here, we use the following rationale: users are sorted in decreasing order of rate requirements. Starting from the user with the highest rate requirement, codes are sequentially assigned to users, until their rate requirements are satisfied or exceeded, in which case the next user is considered. For user j_0, the code $\mathbf{s}_i^* \in \mathcal{S}$, such that

$$\mathbf{s}_i^* = \arg \min_{\mathbf{s}_i \in \mathcal{S}} |r_{min,j_0} - r(\mathbf{s}_i)| \quad (14)$$

is assigned to that user. After each code assignment, rate requirements and set $\mathcal{S}$ are updated. After assignment of all codes, let q_j be the total rate assigned to user j and let $e_j = \max\{0, q_j - r_{min,j}\}$ be the excess rate of j. If there are unsatisfied users, the following procedure is performed: for each user j with $e_j > 0$, we remove the highest rate code $\mathbf{s}_i$ assigned to that user, such that $r(\mathbf{s}_i) < e_j$ (after each removal, e_j's are updated). All such codes are then reassigned to unsatisfied users, starting from the user where code allocation had terminated and applying similar code assignment rules as before.

IV. Simulation Results

For our simulation model, the size of code alphabet is 340 codes. Codes are selected randomly and are classified as follows: 40,100 and 200 codes with spreading gain 16, 32 and 64 respectively. Results are averaged over 50 experiments. User rate requirements are uniformly distributed in a rate interval, so that maximum rate request can be higher than the highest code rate and minimum rate request can be lower than the lowest code rate. For each experiment, 10 different random user rate assignments are used.

For code admission, we measure throughput of admitted codes. Figure 2 illustrates throughput (normalized with chip rate), as a function of SINR threshold for all admission criteria. Criteria 2 and 3 yield similar throughput, which is larger than that of criterion 1. As SINR threshold increases, throughput reduces and all criteria perform similarly. With respect to the number of admitted codes and their rates, we observed that criterion 1 provides fewer and variable rate codes, while the other criteria tend to admit more codes of similar rate and specifically low rate ones. Overall, more low-rate admitted codes turn out to provide better performance than fewer high-rate codes, which implies that a user may be forced to use multiple low-rate codes, although a single high-rate code suffices. If the assignment of multiple codes leads to increased implementation complexity, criterion 1 may be a preferable solution.

We also consider the impact of code admission criteria on feasibility and efficiency of code allocation to users. The latter is quantified by measuring the total residual rate for users that do not satisfy their rate requirements. In Figure 3, we show this residual rate for the three admission criteria for 5, 10 and 20 users. When the average total user request is compared with the throughput graph, the case of 5 users corresponds to an under-loaded system, whereas the case of 20 users corresponds to an over-loaded one. For given user load, results consistently show that criterion 3 has the best performance. As load increases, the performance differences between these criteria become more evident.

In our simulation we randomly selected code alphabets and considered code admission and allocation, based on cross-correlation properties. A more realistic scenario would be to consider a deterministic code alphabet with bounded cross-correlation values, such as a mixture of orthogonal (e.g. Hadamard) and quasi-orthogonal codes. Different criteria for code admission may then be required. For instance, orthogonal codes have zero cross-correlation and are trivially admitted, but any other quasi-orthogonal code may not be admitted, due to high cumulative interference from other orthogonal codes.

V. Conclusion

In this paper, we considered the problem of deterministic code assignment to users, with the objective to achieve high system throughput and satisfy user rate requirements. The determination of the optimal solution in terms of the admissible subset of codes and feasible code allocation to users that yield maximum throughput is a hard optimization problem. Thus, we considered three code admission criteria and provided a heuristic algorithm for code admission and allocation to users.

There exist several directions for future study. The extension of our work to the asynchronous case, which is usually encountered in the up-link, requires modifications in signal reception model and cross-correlation definitions. The design of deterministic variable spreading gain codes is still an open issue. If power control is also incorporated in that design problem or in our model, then these problems become even more challenging.

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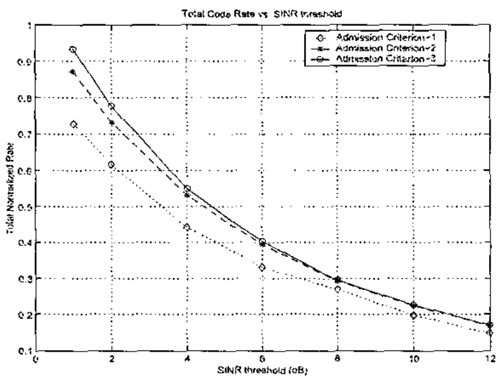

Fig. 2. Total code throughput as a function of SINR threshold γ.

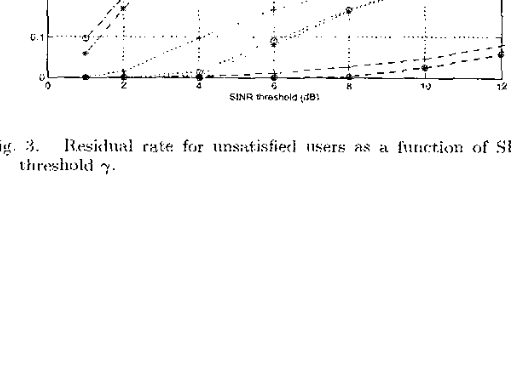

Fig. 3. Residual rate for unsatisfied users as a function of SINR threshold γ.