Abstract—Code-division multiple-access (CDMA) has the potential to support traffic sources with a wide range of quality of service (QoS) requirements. The traffic carrying capacity of CDMA channels under QoS constraints (such as delay guarantee) is, however, less well-understood. In this work, we propose a method based on stochastic network calculus and large system analysis to quantify the maximum traffic that can be carried by a multiuser CDMA network under the QoS constraints. At the physical layer, we have linear minimum-mean square error receivers and adaptive modulation and coding, while the channel service process is modeled by using a finite-state Markov chain. We study the impact of delay requirements, violation probability and the user load on the traffic carrying capacity under different signal strengths. A key insight provided by the numerical results is as to how much one has to back-off from capacity under the different delay requirements.

I. INTRODUCTION

The rapid growth of delay sensitive applications, such as VOIP and IP video, and the scarcity of the radio spectrum require the design of spectrally-efficient systems with quality of service (QoS) support. Direct-sequence code-division multiple-access (DS-CDMA) [1] is an efficient technique that supports flexible scaling of the user population, bursty traffic sources, and a wide range of QoS requirements, such as delay guarantees. A fundamental question is: What is the traffic carrying capacity (throughput) of CDMA networks under the given delay constraints? Answering this question, however, is a challenging task because the existing physical layer channel models do not explicitly take into account the source burstiness and the QoS requirements. Furthermore, the time varying nature of the wireless channel may itself cause severe QoS violations. The above reasons call for a cross-layer approach that can model the link-layer user requirements (e.g. delay guarantee) and at the same time take into account the physical-layer techniques, such as error control coding [2] and multiuser detection [1]. Indeed, predicting the throughput regions for a given delay guarantee is seen as one of the grand challenges in multiuser networks [3].

Two front runner theories for cross-layer modeling of wireless networks are the effective capacity [4], and the stochastic network calculus [5], [6]. The former has been used, e.g., for cross-layer modeling of single user multiple-input multiple-output (MIMO) channels with memory [7]. An attempt was also made in [8] to use efficient bandwidth for cross-layer modeling of wireless CDMA networks with linear minimum-mean square error (LMMSE) receivers. In [8], however, only memoryless channels were considered and the applicability of the proposed approach for quantifying the traffic carrying capacity of CDMA networks under delay constraints is not clear. Stochastic network calculus (NetCal) [9], on the other hand, is a more general theory that has been recently applied for QoS analysis of wireless channels with memory [5], [6].

In this paper, we propose a cross-layer approach to predict the traffic carrying capacity of multiuser CDMA networks under a given delay guarantee. We make use of moment generating function (MGF) based stochastic NetCal that was proposed in [10], and further established and developed in [11]. In stochastic NetCal, a communication system is described by the arrivals at the ingress, the service it provides, and the departures at the egress. It enables easily the consideration of statistical independence between arrivals and system service. In contrast to the previous work, for example, in [8], here the multiuser CDMA channel is considered to have memory. A significant amount of work has been done on link-layer channel modeling of such wireless channels (see [12] and the references therein), especially in the single-user setting. Most of this work builds on the finite-state Markov channel (FSMC) model, which has been successfully applied on the analysis of delay constrained single antenna [13] and MIMO [7] systems, to model the memory in the wireless channels. To the best of our knowledge, however, none of the works based on FSMC considers CDMA networks or uses the stochastic NetCal to analyze the delay constrained throughput of multiuser networks.

The goals and major contributions of this work are as follows. We present a methodology to calculate the network delay constrained throughput of a multiuser DS-CDMA system that employs adaptive modulation and coding (AMC) at the transmitter, and LMMSE multiuser detection at the receiver. The wireless channel is modeled via a FSMC and MGF based NetCal is used to compute the throughput of the system. The formulation is valid for any traffic arrival process for which the MGF or a bound on the MGF exists. In the analysis, we incorporate statistical independence of arriving traffic and the service provided by the channel. We show the impact of the delay guarantee, violation probability and the user load on the throughput under various conditions, such as signal strength and fading speed.
II. The System

The present paper considers a synchronous uplink CDMA channel with \( K \) users. Each mobile station (MS) is equipped with a single transmit antenna and the base station (BS) has a single receive antenna. Perfect channel state information (CSI) is assumed to be available at the BS, while the MSs have no direct access to CSI. At the physical layer, a discrete time signal model indexed by \( n = 1, 2, \ldots \) is considered. We let the number of active users \( K_n \leq K \) at any discrete time instant \( n \) be a random variable, modeling for example the bursty information sources. It is assumed that the BS knows the set of active users at all times.

With the above assumptions, the discrete time received signal after matched filtering and sampling reads \([1], [14]\):

\[
y_n = \sum_{k=1}^{K} h_k s_k + v_n \in \mathbb{C}^M, \quad n = 1, 2, \ldots \tag{1}
\]

where \( b_{k,n} \) is the code symbol transmitted by the \( k \)th user at time instant \( n \). We let \( b_{k,n} = 0 \) if the user \( k \) is not active and \( b_{k,n} \in \mathbb{C} \) otherwise. The code symbols of the active users are assumed to be independent with zero mean and unit variance. The length (the spreading factor) of the signature sequences \( \{s_k\}_{k=1}^{K} \) is \( M \) for all users. The random vector \( v \sim \mathcal{CN}(0, \sigma^2 I_M) \) represents samples of additive white Gaussian (AWGN), where \( I_M \) denotes the identity matrix of size \( M \times M \), and \( \mathcal{CN}(\mu, \Psi) \) stands for the circularly symmetric complex Gaussian (CSCG) distribution with mean \( \mu \) and covariance \( \Psi \). The channels between the MSs and the BS are assumed to be block fading (see, e.g., \([15]\)) with a fixed coherence time. Throughout the paper we assume that the code words transmitted by the users are shorter than the coherence time, and omit the block index for notational simplicity. The fading coefficients \( h_k \sim \mathcal{CN}(0, 1) \) for all \( k = 1, \ldots, K \) are considered to be independent and identically distributed (IID), but extension to unequal average received powers is straightforward. Random spreading \([1], [14], [16]\) is assumed to be employed at the MSs, so that the signature sequences \( \{s_k\}_{k=1}^{K} \) are IID CSCG random vectors \( s_k \sim \mathcal{CN}(0, \frac{1}{M} I_M) \).

For future convenience, we define the user load of the system at time instant \( n \) as the ratio \( \alpha_n = K_n/M \), and the average received signal to noise ratio (SNR) as \( \text{SNR}_{\text{avg}} = 1/\sigma^2 \).

A. LMMSE Receiver for Multiuser CDMA

Multiuser receivers mitigate, in addition to background noise, the interference between the users. It is well understood that the choice of multiuser detector has a significant effect on the system capacity (see, e.g., \([1], [14], [16]\)). The effect of delay constraints on the throughput of the CDMA network is, however, not yet well understood. Here we consider the impact of such effects on the throughput obtained by a multiuser CDMA system equipped with the LMMSE receiver \([1]\).

Extensions to other receivers are also possible, but they have been omitted from the present paper due to space constraints.

Let us consider without loss of generality the detection of code symbol \( b_{1,n} \) of the first user when the mobile stations \( k = 1, \ldots, K_n \leq K \) are active. The LMMSE receiver forms the decision variable for the first user at time instant \( n \) as \( z_{1,n} = c_{1,n} y_t \), where \( c_{1,n} \in \mathbb{C}^N \) and the superscript \((\cdot)^H\) denotes for the conjugate transpose of the matrix. If the BS knows perfectly the channel coefficients \( \{h_k\}_{k=1}^{K} \) and the signature sequences \( \{s_k\}_{k=1}^{K} \) of all users, we can define

\[
S_{1,n} = [s_2 \cdots s_{K_n}] \in \mathbb{C}^{M \times (K_n-1)}, \tag{2}
\]

\[
D_{1,n} = \text{diag}(\{|h_2|^2, \ldots, |h_{K_n}|^2\}) \in \mathbb{C}^{(K_n-1) \times (K_n-1)}, \tag{3}
\]

\[
M_{1,n} = S_{1,n} D_{1,n} s_1^H + \sigma^2 I_{K_n-1} \in \mathbb{C}^{(K_n-1) \times (K_n-1)}, \tag{4}
\]

and the LMMSE detector for the first user becomes \([1], [14]\):

\[
c_{1,n} = \frac{h_1}{1 + |h_1|^2 s_1^H M_{1,n}^{-1} s_1}. \tag{5}
\]

The conditional output SINR for the LMMSE receiver reads

\[
\gamma_{1,n} \left( \{s_k\}_{k=1}^{K}, \{h_k\}_{k=1}^{K} \right) = |h_1|^2 s_1^H M_{1,n}^{-1} s_1. \tag{6}
\]

For the purpose of the cross-layer analysis, however, \([6]\) is not a convenient starting point due to its dependence on the signature sequences and the channels of all active users.

B. Large System Limit and the Decoupling Principle

To simplify the physical layer model, we consider throughout the paper the large system limit in which both the number of active users \( K_n \leq K \) and the spreading factor \( M \) grow without bound with a fixed ratio \( \alpha_n = K_n/M \), for all \( n = 1, 2, \ldots \). In this asymptotic region, the multiuser CDMA channel \([1]\) decouples under very general conditions to a set of single-user channels \([14], [17]\) that do not depend on the signature sequences \( \{s_k\}_{k=1}^{K} \). For the case of LMMSE receiver considered in Section \([14], [17]\), the SINR after multiuser detection simplifies in the large system limit to \([14], [17]\):

\[
\gamma_{1,n} = p_1/\beta_{1,n}, \tag{7}
\]

where \( p_1 \) represents the instantaneous channel power in the decoupled single-user channel and is drawn according to the probability density function (PDF)

\[
f(p_1) = e^{-p_1}, \quad p_1 \geq 0. \tag{8}
\]

The noise variance \( \beta_{1,n} \) in the equivalent single-user system is the solution to the fixed point equation

\[
\beta_{1,n} = \sigma^2 + \alpha_n \int_0^\infty \frac{p \beta_{1,n}}{p + \beta_{1,n}} e^{-p} dp. \tag{9}
\]

Since the interference becomes Gaussian in the large system limit \([17]\), the decision variables \( z_{1,n} \) are statistically equivalent to the received symbols of the single-user (su) channel

\[
z_{1,n}^\text{su} = \sqrt{\beta_{1,n}} b_{1,n} + n_{1,n}^\text{su}, \quad n = 1, 2, \ldots \tag{10}
\]

where \( n_{1,n}^\text{su} \sim \mathcal{CN}(0, \beta_{1,n}) \), \( n = 1, 2, \ldots \) are mutually independent samples of Gaussian noise. For later use, we denote \( \gamma_{1,n} = E[p_1] \{\gamma_{1,n}\} = 1/\beta_{1,n} \) for the post-detection SINR \([7]\) that is averaged over the channel gain \( p_1 \).

Remark 1: The fixed point equation \([9]\) is easy to solve iteratively and is always guaranteed to converge. Note also that
conditions. However, designing arbitrary rate codes is difficult and as the number of code books $L$ grows, a reliable and very high rate feedback channel is needed for code book selection. Thus, the number of transmission modes $L$ is in practice small.

Remark 2: The authors in, e.g., [7], [13] propose to simulate specific AMC schemes in AWGN channel and use parameter fitting to derive “analytical” error probabilities for them. Such results are, however, heavily dependent on the chosen error control codes. We consider instead the modulation constrained capacity (11) that gives an upper bound for all coding schemes with the same modulation sets and code rates. With the new code designs [2], we expect our results to provide a close description of modern wireless systems.

III. DELAY CONSTRAINED THROUGHPUT ANALYSIS

In this section we concentrate on the decoupled single-user channel (10) of the first user and omit both the user $k$ and the time $n$ indexes for notational convenience. The wireless channel service process in the block fading channel with AMC is modeled using an $L$-state finite state Markov chain (FSMC) where the block length (in seconds) is denoted by $T_b$. Each of the transmission modes is mapped to the corresponding FSMC state. Let $P_e = [p_{l,l'}]$ be the $L \times L$ transition matrix of the FSMC. Assuming slow fading and a relatively small value of $T_b$, we have $p_{l,l'} = 0$ for all $l \neq l'$. The adjacent state transition probabilities are determined as [19]

$$
\left\{ \begin{array}{ll}
    p_{l,l+1} \approx \frac{N(\gamma)}{\pi} T_b, & l = 1, 2, \ldots, L - 1, \\
    p_{l,l-1} \approx \frac{N(\gamma)}{\pi} T_b, & l = 1, 2, \ldots, L
\end{array} \right.
$$

(14)

where $N(\gamma)$ denotes the level crossing rate (LCR) at the SNR value of $\gamma$. The remaining transition probabilities are given as

$$
\left\{ \begin{array}{ll}
    p_{1,1} = 1 - p_{1,2} \\
    p_{L,L} = 1 - p_{L,L-1} \\
    p_{l,l} = 0, & l = 2, 3, \ldots, L - 1
\end{array} \right.
$$

(15)

The level crossing rate reads for $\Gamma \geq 0$ [19]

$$
N(\Gamma) = \sqrt{\frac{2\pi\Gamma}{\gamma}} f_m \exp \left( -\frac{\Gamma}{\gamma} \right),
$$

(16)

where $f_m = v/\omega$ is the maximum Doppler frequency of the channel, defined in terms of the vehicle speed $v$ and the wavelength $\omega$ of the transmitted signal. The stationary probability $\pi_l$ of the FSMC being in state $l$ is given as

$$
\pi_l = \int_{\Gamma_l}^{\Gamma_{l+1}} f(\gamma) \, d\gamma = \exp \left( -\frac{\Gamma_l}{\gamma} \right) - \exp \left( -\frac{\Gamma_{l+1}}{\gamma} \right).
$$

(17)

The PDF of the instantaneous received SNR $f(\gamma)$ of the single-user channel (10) is statistically equivalent to the large system post-detection SINR of (1), and given by

$$
f(\gamma) = \frac{1}{\gamma} \exp \left( -\frac{\gamma}{\gamma} \right), \quad \gamma \geq 0,
$$

(18)

where $\gamma = E_p \{ \gamma_{1,n} \} = 1/\beta_{1,n}$. We remind the reader that the average SNR $\overline{\gamma}$ is in fact a function of time $n = 1, 2, \ldots$. 

\[\beta_{1,n}\] has time dependence only through $\alpha_n$, so that in the large system limit only the size of the active user set matters — not which users are in it. For the purpose of cross-layer analysis, we shall therefore concentrate on the equivalent single-user channels defined by (7)–(10), where $\{p_k\}_{k=1}^K$ and $\{n_{k,n}\}_{k=1}^K$ are all mutually independent random variables.
based channel service process as

\[ d^*_\lambda = \inf_{\theta > 0} \left\{ \inf_{\tau \geq 0} \left[ \tau \cdot \frac{1}{\theta} \left( \ln \sum_{s=\tau}^{\infty} M_A(\theta, s - \tau) \tilde{M}_S(\theta, s) - \ln \varepsilon \right) \right] \leq 0 \right\}, \]

(22)

the noise variance at the receiver \( \sigma^2 \), and the instantaneous user load \( \alpha_n \), through the fixed point equation (9).

A. Main Result

The moment generating function (MGF) of a stationary process \( X(t) \) is given by \( M_X(\theta, t) = E[e^{\theta X(t)}] \). In the sequel, we denote \( \tilde{M}_X(\theta, t) = M_X(-\theta, t) \) for the parameters \( \theta > 0 \), \( t \geq 0 \). The discrete time arrivals and service of the channel are assumed to be independent stationary random processes given by the cumulative processes \( A(0, t) \) and \( S(s, t) \) respectively. For all real \( \theta \), the corresponding MGFs are \( M_A(\theta, t) \) and \( \tilde{M}_S(\theta, t) \), respectively. Furthermore, let \( N_0 \) denote the number of information bits per an upper layer data block and \( W \) the system bandwidth. Omitting again both the user and the time indexes for notational convenience, we can then write the number of data blocks transmitted in state \( l \) of the FSMC based channel service process as \( \tilde{R}_l = R_l T_b W/N_0 \).

**Lemma 3.1**: The MGF of the random process \( S(t) \) described by a homogeneous Markov chain with transition matrix \( P_c \) and stationary state distribution vector \( \pi \), is given for \( \theta > 0 \) and \( t \geq 0 \) by

\[ \tilde{M}_S(\theta, t) = \pi(\tilde{R}(\theta) P_c)^{e-1} \tilde{R}(\theta) 1, \]

(19)

where \( 1 \) is column vector of ones and

\[ \tilde{R}(\theta) = \text{diag}(e^{\theta R_1}, \ldots, e^{\theta R_K}). \]

(20)

The steady state vector \( \pi = [\pi_1 \pi_2 \cdots \pi_L] \) is given in (17) and \( P_c \) is obtained from (14) – (15).

**Proof**: We refer the interested reader to (10). ■

We denote the traffic arrival rate by \( \lambda \) while \( d^*_\delta \) represents a bound with violation probability \( \varepsilon \) on the delay. We can only provide a delay guarantee \( \delta^* \) if \( d^*_\delta \leq \delta^* \).

**Proposition 3.2**: The delay constrained throughput \( \lambda_{\delta} \) of a DS-CDMA system under a delay guarantee \( \delta^* \) is given as

\[ \lambda_{\delta} = \alpha \cdot \max \{ \lambda \mid d^*_\lambda \leq \delta^* \}, \]

(21)

where \( d^*_\lambda \), assuming FIFO scheduling, is given in (22) at the top of the page and \( \tilde{M}_S(\theta, t) \) is given by (19).

**Proof**: We refer the interested reader to (11). ■

**Remark 3**: The delay bound (22) is calculated using stochastic NetCal approach (11). MGF for a variety of arrival models is available in the literature (10) but finding the MGF of the service process \( \tilde{M}_S(\theta, t) \) is a challenging task. We address this challenge by making use of Lemma 3.1 to calculate \( \tilde{M}_S(\theta, t) \). Having obtained \( \tilde{M}_S(\theta, t) \), a stochastic bound on the delay \( d^*_\delta \) in (22) can be obtained using Chernoff’s bound, Boole’s inequality and applying the technique in (11).

We next use the result in this section to calculate the delay constrained throughput of a multilayer DS-CDMA system. Before closing this section, we present a definition which will be used in the next section. The maximum carried traffic without the delay constraints in bps is given by

\[ C_{\text{lim}} = \alpha W \sum_{l=1}^{L} R_l \pi_l, \]

(23)

IV. APPLICATION AND NUMERICAL RESULTS

In the numerical results, we consider the AMC setup given in Table I. The transmission modes follow the HIPERLAN/2 specification (see, e.g., (7), (18)). The parameter \( \gamma_l \) in Table I denotes the SNR point in decibels (dBs) where the \( l \)th mode is switched on. The physical layer of the system is parameterized by using a \( W = 20 \) MHz channel. The base time unit is chosen to be \( T_b = 2 \) ms and a block transmission with fixed duration \( T_b \) is assumed. The size of the upper layer data blocks is fixed to \( N_0 = 10 \) 000 bits, but the number of information bits transmitted per fading block varies depending upon the selected AMC scheme. The rate matrix \( R(\theta) \) can be read from the Table I. The infinite sum in the delay bound formula (22) is computed for the first 4000 units of time.

The framework discussed earlier enables the derivation of delay constrained throughput of a various number of traffic sources whenever the MGF exists. In this work we use a periodic source for the discrete time model that generates arrival traffic. Such a traffic source with period \( \tau \) produces \( \delta \) units of workload (data blocks) and its MGF reads \( (5) \)

\[ M_A(\theta, t) = e^{\theta \delta} \left( 1 + \left( \frac{t}{\tau} - \left\lfloor \frac{t}{\tau} \right\rfloor \right) (e^{\theta \delta} - 1) \right), \]

(24)

where \( t \geq 0 \) and \( \theta > 0 \). Here we set \( \delta = 1 \) and use the number of generated data blocks \( \delta \) to set the arrival rate \( \lambda \).

Fig. 1 depicts throughput as a function of delay guarantee \( \delta^* \) for different delay bound violation probabilities \( \varepsilon \). One can observe the decrease in system throughput as the violation probability and \( l \) or the delay guarantee get(s) tighter.

The impact of the average received SNR (SNRavg = 1/\( \sigma^2 \)) on the throughput is studied in Fig. 2. As expected, increasing the average received SNR leads to an improvement in the throughput, as seen in the classical information theoretic results as well. For the considered system this is due to the fact that, the higher average received SNR increases the likelihood of a better channel (note that here this effect comes from (7), (9), (17) and (18)) at any given time instant and, thus, allows

| Modes | \( M_l \) | \( R_l \) (bps/Hz) | \( \gamma_l \) (dB) |
|-------|--------|-----------------|---------------|
| 0     | BPSK   | 0               | -\infty       |
| 1     | BPSK   | 0.5             | -2.80         |
| 2     | QPSK   | 1               | 0.19          |
| 3     | QPSK   | 1.5             | 3.39          |
| 4     | 16-QAM | 2.25            | 6.20          |
| 5     | 16-QAM | 3.7             | 9.30          |
| 6     | 64-QAM | 4.5             | 14.37         |

**TABLE I**

TRANSMISSION MODES
for higher rate code books to be used at the transmitters on average. This can be clearly seen by observing the steady state for higher rate code books to be used at the transmitters on time varying channel. Channel memory is modeled by a finite capacity to meet the delay guarantee.

Finally, Fig. 3 depicts the delay constrained capacity as a function of the maximum user load \( \alpha = K/M \). With the delay constraint, the system throughput behaves similarly to the information theoretic case (see, e.g., [16] Fig. 1), but the optimum user load shifts towards zero when the delay guarantee gets tighter. The non-linear behavior of the throughput as a function of the maximum user load is due to the interplay between \( \alpha \), \( \varepsilon \) and \( f_m \) dB. We also see that the higher the user load is, the further we have to back-off from the capacity to meet the delay guarantee.

V. CONCLUSIONS AND FUTURE WORK

In this paper we formulate a method to find the delay constrained throughput of a multiuser DS-CDMA system with time varying channel. Channel memory is modeled by a finite state Markov chain. We present numerical results where we quantify the impact of increasing the delay guarantee and the user load on the delay constrained throughput for varying signal strength. This work finds application in performance evaluation of wireless networks where the maximum throughput for a given delay guarantee and amount of resources is of interest. While in this work, we only used periodic source to illustrate the results, the same methodology can be applied to any traffic source with known MGF.

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