Data Throughput Analysis for the Uplink of CDMA Cellular Networks

Rodolpho C. G. F. de Mello and Celso de Almeida

***Abstract*— This article analyses the data throughput of the uplink of a DS-CDMA cellular network, using random and Walsh spreading sequences, the matched filter and multiuser detector decorrelator (MUD-D). The mathematical modelling of the system described above takes into consideration an additive white gaussian noise channel with exponential path loss, perfect power control and internal and external co-channel interference. Within this context different modulations such as QPSK and M-QAM (16, 64 and 256-QAM) are used.**

***Keywords*— Data Throughput, DS-CDMA, Random Spreading Sequences, Walsh Spreading Sequences, Matched Filter, MUD-D, M-QAM, Co-Channel Interference.**

I. Introduction

Great efforts are being employed in the treatment of the voice and data demand in the new generations of cellular mobile networks. Therewith, some improvements are being requested in order to achieve an increased data rate per user, leading to, consequently, an increase in the data throughput related to the cellular network as a whole.

The data throughput of a cellular network is a measure of the data flow, in bits per second, due to each active user in the network or even in a single cell. Thus, the main solutions to achieve such an increase in the data throughput of a cellular network generally revolve around both the increase of the number of active users and the data rate per active user. However, changing those parameters is not a trivial task due to, mainly, the existence of some system requirements, as the bit error rate and the maximum transmitted power, that must be kept within a range of acceptable levels. Concerning the increase of data rate per user and spectral efficiency, some works, like [1], have considered using high order QAM modulations as a potential solution to this problem, even though they need a higher E_b/N_0 ratio to work well.

The technique that deals with the allocation of users in a communication channel is called multiple access technique. This method consists in sharing the channel resources with the users without causing any excessive interference among them [2]. A multiple access method that, among other advantages, include the allocation of a large number of users due to the use of the spread spectrum technique is the so called CDMA (Code-Division Multiple Access), which was introduced in the mobile communications in the 90's with the IS-95 standard, also called CDMAone, which is part of the second generation of cellular mobile networks. That method consists in sharing the same frequency spectrum by several users, which transmit their data simultaneously and are distinguished only by spreading sequences that are assigned individually. This way, this work aims at the performance analysis of a DS-CDMA cellular network from the perspective of the network data throughput, taking into consideration the choice of the spreading sequences, the modulation and the detection technique.

At first, it will be analysed the random and Walsh spreading sequences and the matched filter and multiuser (MUD-D) detection methods. The modulations taken into consideration are the QPSK (Quadrature Phase-Shift Keying) and QAM (Quadrature Amplitude Modulation). Such comparisons are performed by considering the uplink of a bandpass synchronous DS-CDMA system, with a perfect power control and the presence of internal and external co-channel interference.

II. Basic Concepts

A. Power Control

The CDMA system considered in this work takes into account a perfect power control, i.e, a given base station (BS) always receives the same power from the users located at the same cell, regardless their position. The propagation model considered in this paper takes into account an exponential path loss, given by:

$$P_{Rn} = P_{Tn} r_n^{-\beta} \tag{1}$$

where P_{Rn} is the received power by the BS from the n-th user, P_{Tn} is the transmitted power due to the n-th user, r_n is the distance between the n-th user and the BS and β is the path loss exponent.

It is known that in the case of power control, a power compensation is used at the transmitter according to a path loss estimation, so that the received power from the users is the same independently of their distance to the BS. Therefore, the power transmitted by the n-th mobile station (MS) is considered to be equal to $P_0 r_n^{\beta}$, so that the power that arrives at the BS is always equal to P_0.

The probabilistic distribution of the users in the cell is given according to:

$$f_R(r) = \frac{2r}{R^2},\ for\ \ 0 \le r \le R \tag{2}$$

$$f_\Phi(\phi) = \frac{1}{2\pi},\ for\ \ 0 \le \phi \le 2\pi \tag{3}$$

where r and ϕ are the polar coordinates for the user's position in relation to its respective BS and R is the cell radius, given in meters (m).

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For the case in which the transmitting user is located in any of the neighbor cells, the distance D between the interfering user and the BS of the central cell is defined as [3]:

$$D_i = \sqrt{\left(\sqrt{3F}R + r_i \cos\phi_i\right)^2 + (r_i \sin\phi_i)^2} \tag{4}$$

where F corresponds to the reuse factor.

B. Data Throughput

The data throughput considered in this work consists in the sum of the bit rates related to all the N users located at the central cell. Due to the power control, this work considers that all the users transmit with the same bit rate and, consequently, the data throughput can be expressed as:

$$\nu = NR_b \tag{5}$$

Primarily, to calculate the data throughput it is necessary to define some important parameters, as the channel bandwidth and the processing gain related to the use of the spread spectrum technique, defined as:

$$G = \frac{T_s}{T_c} = \frac{R_c}{R_s} \tag{6}$$

where $T_s = 1/R_s$ is the symbol duration, R_s is the symbol rate, $T_c = 1/R_c$ is the chip duration and R_c is the chip rate.

According to the Nyquist criterion, the maximum data rate with no intersymbol interference (ISI) in a bandpass communication system with spread spectrum bandwidth B is equal to GR_s. Thus, using that $R_s = R_b/\log_2 M$, the spread spectrum bandwidth expression can be written as:

$$B = G\frac{R_b}{\log_2 M} \tag{7}$$

Then, using (7) and that $P_R = E_b R_b$, the ratio between the power received by the BS from a given user, and the power spectral density of the additive white gaussian noise is given by:

$$\frac{P_0}{N_0} = \frac{E_b}{N_0} R_b \tag{8}$$

where, according to the power control, the received power (P_R) from a given user is always equal to P_0.

III. DS-CDMA WITH MATCHED FILTER FOR M-QAM MODULATIONS

The simplest CDMA signals detection strategy is the matched filter [4] defined in [2]. Although it is considered the best signal detection technique in AWGN (Additive White Gaussian Noise) channels, it presents an important performance degradation due to the multiple access interference (MAI) [5].

A direct sequence CDMA communication system (DS-CDMA) with matched filter and M-ASK modulation has its transmitter and receiver depicted in the Fig.1.

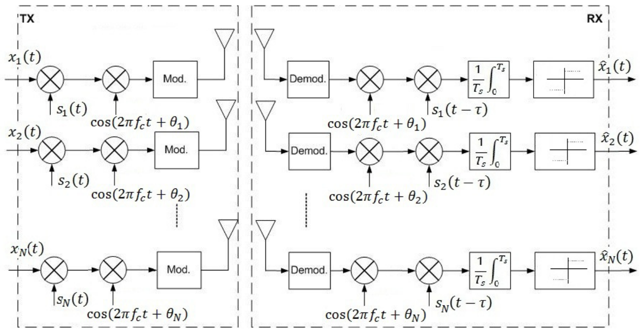

Fig. 1. DS-CDMA Scheme with Matched Filter for M-ASK Modulation.

A. Random Spreading Sequences

Considering the uplink of a synchronous DS-CDMA system with matched filter, random spreading sequences and M-ASK modulation in a cell with N users, the signal $r(t)$ at the input of the receiver is given by:

$$r(t) = \sum_{n=1}^{N} A_n \xi_n s_n(t) \cos(2\pi f_c t + \theta_n) + n(t) \tag{9}$$

where A_n and ξ_n are, respectively, the amplitude and the symbol for the n-th user, $s_n(t)$ is the spreading sequence related to the n-th user, f_c is the carrier frequency, θ_n is the phase received of the carrier and $n(t)$ is the additive white gaussian noise with unilateral power spectral density equal to N_0. The M-ASK symbols admit values according to $\xi_n = (2m - 1 - M)/2$, where m varies from 1 to M.

The sample at the matched filter output of the k-th user can be written as:

$$\begin{aligned}\hat{x}_k(T_s) &= \frac{A_k \xi_k}{2} + \sum_{n=1, n\neq k}^{N} \frac{A_n}{2} \xi_n \cos(\theta_n - \theta_k) R_{nk}(0) \\ &+ \frac{1}{T_s}\int_0^{T_s} n(t) s_k \cos(2\pi f_c t + \theta_k) dt\end{aligned} \tag{10}$$

where $R_{nk}(0) = \frac{1}{T_s}\int_0^{T_s} s_n(t) s_k(t) dt$ is the synchronous cross-correlation function between the sequences $s_n(t)$ and $s_k(t)$, and, due to the fact that the pulse shape in baseband is rectangular, we used that $\frac{1}{T_s}\int_0^{T_s} s_n^2(t) dt = 1$.

The first term of (10) corresponds to the signal transmitted by the k-th user, while the second and third terms correspond, respectively, to the MAI and to the noise contribution.

Considering that the symbol ξ_k was sent, the mean value of $\hat{x}_k(T_s)$ can be written as:

$$\mu_x = \frac{A_k \xi_k}{2} \tag{11}$$

The variance of the MAI is given by:

$$\sigma^2 = A^2 \frac{M^2 - 1}{96} \frac{N-1}{G} \tag{12}$$

where it was considered that $\overline{\xi_n^2} = (M^2 - 1)/12$, $\overline{\cos^2(\theta_n - \theta_k)} = 1/2$ and $\overline{R_{nk}^2(0)} = 1/G$ for the random synchronous case [6].

The noise variance, is given by:

$$\sigma^2 = \frac{N_0}{4T_s} \tag{13}$$

Since a M-QAM signal can be formed by the cartesian product between two $\sqrt{M}$-ASK signals [7], the Signal-to-Noise plus Interferece Ratio (SNIR) expression for the M-QAM modulation can be expressed as:

$$\gamma = \frac{1}{\frac{(M-1)}{3}\frac{N-1}{G} + \frac{N_0}{E_b}\frac{2(M-1)}{3\log_2 M}} \tag{14}$$

where it was used that the energy per symbol for the M-ASK modulation is $E_s = \frac{(M^2-1)}{24}A^2T_s$ and that the BER approximation $P_b \approx Q\left(\sqrt{2\gamma}\right)$ assumed in this work is due to the fact that both the internal and the external interference were treated as gaussian random variables, once it is considered to be a good approximation when it comes to high values of processing gain and a great number of users.

For the case in which there is external cellular interference, in addition to the internal interference initially considered, i.e, when there are interfering cells in the system, the term $\sum_{n=1}^{N}\frac{A_n}{2}\xi_n\cos(\theta_n-\theta_k)R_{nk}(kT_c)(r_n/D_n)^{\beta/2}$, is added to (10), where the ratio $(r_n/D_n)^{\beta/2}$ corresponds to the path loss of the relation between the distance (r) of the n-th interfering user to its respective BS and the distance (D) from the n-th interfering user to the BS of the considered cell.

The expression for the SNIR, considering M-QAM modulations, is then modified as follows:

$$\gamma = \frac{1}{\frac{(M-1)}{3}\frac{N-1}{G} + C\frac{N}{G}\frac{(M-1)}{3}\lambda + \frac{N_0}{E_b}\frac{2(M-1)}{3\log_2 M}} \tag{15}$$

where C is the number of interfering cells and $\lambda = \overline{\left(\frac{r}{D}\right)^{\beta}}$ is the factor relating the internal co-channel interference to the external co-channel interference.

B. Walsh Spreading Sequences

The Walsh spreading sequences holds the orthogonality property, i.e, the cross correlation pairwise is null $\overline{R_{nk}^2(0)} = 0$. The IS-95 standard uses this type of spreading sequences for multiplexing of users in the downlink, where the channel is essentially synchronous.

The Walsh sequences can be obtained through the Hadamard matrix as follows [6]:

$$\mathbf{W_{2G}} = \begin{bmatrix} W_G & W_G \\ W_G & \overline{W_G} \end{bmatrix} \tag{16}$$

where $\overline{W_G}$ is a sub-matrix GxG composed of elements ± 1 and it symbolizes the logical denial of the sub-matrix W_G.

In this case, using Walsh spreading sequences in an AWGN channel with M-QAM modulation, besides considering only the internal co-channel interference which, in this case, is null, the SNIR can be represented as:

$$\gamma = \frac{E_b}{N_0}\frac{3\log_2 M}{2(M-1)} \tag{17}$$

where, $N \leq G$, i.e, in this case there is a limit in the number of users covered by the cell. This limit is related to the size (G) of the spreading sequences, since W_G is a square matrix.

Again, for the case in which there is internal and external co-channel interferences, the Walsh sequences behave similar to the random sequences, once the external co-channel interference arrives at the receiver with different delays depending on the position of the users. Thereby, the SNIR is given by:

$$\gamma = \frac{1}{C\frac{N}{G}\frac{(M-1)}{3}\lambda + \frac{N_0}{E_b}\frac{2(M-1)}{3\log_2 M}} \tag{18}$$

IV. DS-CDMA WITH MUD-D DETECTOR FOR M-QAM MODULATIONS

The multiuser detector decorrelator, or simply MUD-D, is a sub-optimum multiuser detection technique that belongs to the class of the linear detectors. Fig. 2 shows the receiver for a DS-CDMA system with the MUD-D multiuser detector.

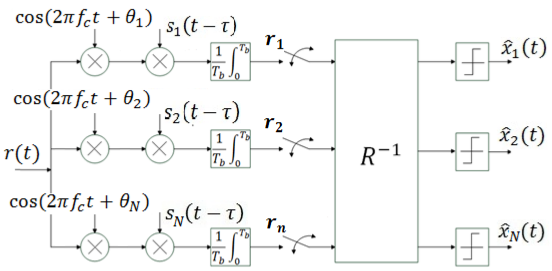

Fig. 2. Scheme of the DS-CDMA Receiver with MUD-D for M-ASK Modulations.

The samples at the output of the bank of matched filters are given by:

$$\mathbf{r} = \frac{1}{2}\mathbf{RA}\xi + \mathbf{n} \tag{19}$$

where $\mathbf{R}$ is the cross correlation matrix given by:

$$\mathbf{R} = \begin{cases} 1, & if\ n = k \\ R_{nk}, & if\ n \neq k \end{cases} \tag{20}$$

and $\mathbf{A}$ and ξ are, respectively, the diagonal matrix of the amplitudes and the vector of symbols referring to the users, and $\mathbf{n}$ is a gaussian random vector of null mean and matrix of covariance equal to $\sigma^2\mathbf{R}$.

The MUD-D detection method consists in the multiplication of the samples, after the bank of matched filters, by the inverse correlation matrix $\mathbf{R}^{-1}$, by considering that $\mathbf{R}$ is invertible.

Accordingly, the samples at the output of the MUD-D are given by:

$$\mathbf{R}^{-1}\mathbf{r} = \frac{1}{2}\mathbf{A}\xi + \mathbf{R}^{-1}\mathbf{n} \tag{21}$$

where the sample of the k-th user gets free from MAI, however, the noise is increased by the factor R_{kk}^{-1}.

As (21) is considered to be a gaussian random variable, its mean is equal to the matched filter's case (11), however, its variance is given by:

$$\sigma^2 = E\left[\left(\mathbf{n}\mathbf{R}^{-1}\right)\left(\mathbf{n}\mathbf{R}^{-1}\right)^T\right] = \frac{N_0}{4T_s} R_{kk}^{-1} \qquad (22)$$

Considering that a M-QAM symbol is transmitted, the expression for the SNIR, in this case, is given by:

$$\gamma = \frac{E_b}{N_0} \frac{3\log_2 M}{2(M-1)} \left(1 - \frac{L}{2}\right) \qquad (23)$$

where the term $1/\overline{R_{kk}^{-1}} = 1 - L/2$, according to [8],[9], for the bandpass case , is defined as the mean asymptotic multiuser efficiency and $L = (N-1)/G$ is the load factor of the system.

In the presence of external cellular interference, the SNIR can be represented as:

$$\gamma = \frac{1}{C\frac{N}{G}\frac{(M-1)}{3}\left(\frac{1}{1-\frac{L}{2}}\right)\lambda + \frac{N_0}{E_b}\frac{2(M-1)}{3\log_2 M}\left(\frac{1}{1-\frac{L}{2}}\right)} \qquad (24)$$

V. RESULTS

Using the definitions for the cases considered in the above sections, it is possible to analyse the data throughput of a DS-CDMA cellular network taking into account a scenario defined in the Table I.

TABLE I

DS-CDMA SYSTEM PARAMETERS

BER_{min}	Rb_{min}	B	Pt_{max}	R	C
10^{-4}	10 kb/s (voice)	5 MHz	0.5 W	1 km	6

Considering the power requirement (Pt_{max}) and the cell radius (R) specified above, and the path loss exponent $\beta = 4$, according to (1), we have that $P_0 = 0.5$ pW. Similarly, given the requirements and the BER expressions above for each case, considering $N_0 = -174$ dBm/Hz, it can be obtained the minimum SNIR requirements for each modulation.

From [10], using C, specified in Tab. I, we have that the product $C\lambda$, referring to the total decreasing factor of the external interference in relation to the internal, is equals to 0.69. Besides that, in this work, it is considered synchronism in the uplink of a DS-CDMA cellular network in order to make possible the use of Walsh sequences.

Fig. 3 shows the data throughput versus the number of users in a DS-CDMA system using random sequences and matched filter, considering internal and external interference for E_b/N_0 equal to 30 dB. It can be observed that when using matched filter the lower order modulations present higher data throughput. Accordingly, it can also be noticed that the data throughput is practically halved as N grows when there are interfering cells. As it can be seen, the use of high order modulations become impractical for a E_b/N_0 ratio of 30 dB.

Fig. 4 illustrate the scenario of the data throughput versus the number of users in a DS-CDMA system with matched filter and Walsh spreading sequences, for E_b/N_0 equal to 30 dB. It is possible to observe, in the case with only one cell, that the data throughput remains constant and raises with $\log_2 M$, as we elevate the order of the QAM modulation. Furthermore, the higher order modulations present a better performance, as expected. When the existence of interfering cells is considered, the number of active users covered by the cell starts decreasing and the higher order QAM modulations present a higher loss in this sense. However, the data throughput is kept constant as in the the case without external cellular interference.

Fig. 5 illustrate the data throughput of a DS-CDMA system with MUD-D detector and random sequences for E_b/N_0 equal to 30 dB. It can be noticed that, mainly, the data throughput doubles when there are no interfering cells. Besides that, differently from the case with matched filter and Walsh spreading sequences, the use of random sequences makes the number of possible sequences increase to 2^G. It is also apparent that higher order modulations, as well as Walsh spreading sequences, present a superior performance as compared to the lower order modulations. However, when the external co-channel interference is present, the MUD-D presents a strong degradation in the data throughput. That is due to the fact that when the external cellular interference is present, besides the noise contribution raised by R_{kk}^{-1}, there is also the interfering users contribution raised by the same factor. It can also be noticed that, in the presence of the external interference, the higher order modulations loses in performance and tend to behave similar to the case with matched filter and random spreading sequences.

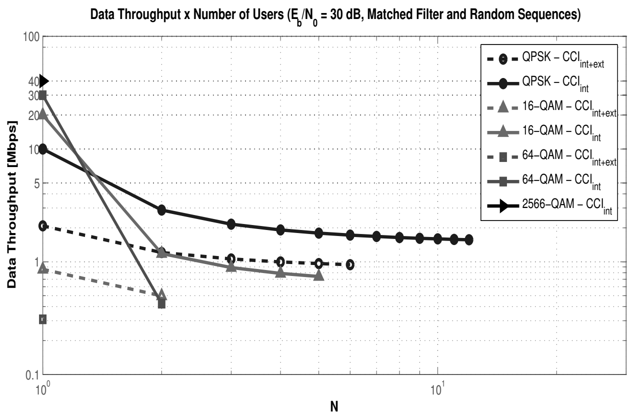

Fig. 3. Data Throughput Versus the Number of Users for a DS-CDMA System with Matched Filter and Random Spreading Sequences for $E_b/N_0 =$ 30 dB and QPSK, 16, 64 and 256-QAM Modulations.

VI. CONCLUSIONS

In this work, the DS-CDMA performance in terms of data throughput is analyzed.

Moreover, in this article, SNIR expressions for the matched filter and the MUD-D detector for M-QAM modulations is proposed considering random and Walsh spreading sequences and the presence of external and internal co-channel interference.

It is shown that a CDMA system with matched filter and random spreading sequences does not present interesting characteristics in terms of data throughput due to the weak performance of higher order modulations, making its deployment in cellular networks, which aim at the raise of the data

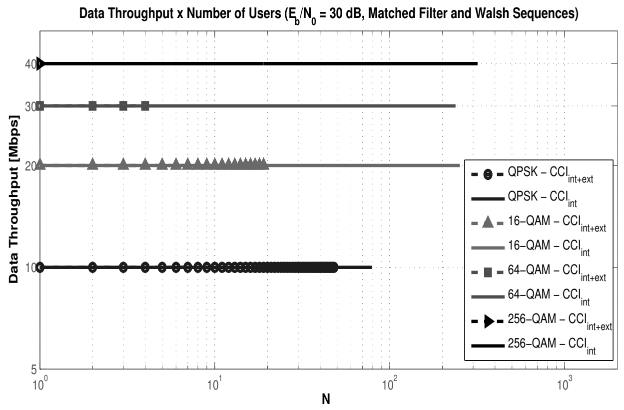

Fig. 4. Data Throughput Versus the Number of Users for a DS-CDMA System with Matched Filter and Walsh Spreading Sequences for $E_b/N_0 = 30$ dB and QPSK, 16, 64 and 256-QAM Modulations.

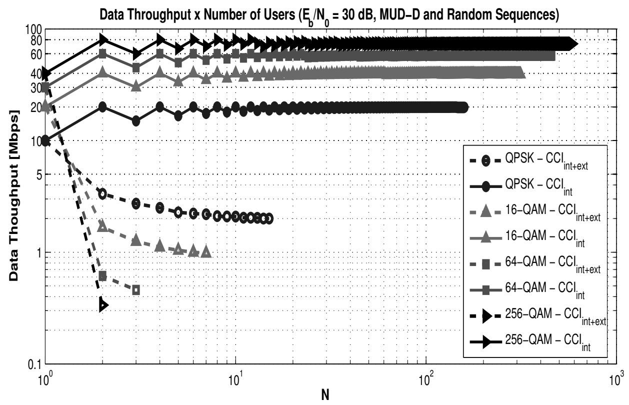

Fig. 5. Data Throughput Versus the Number of Users for a DS-CDMA System with MUD-D Detector and Random Spreading Sequences for $E_b/N_0 = 30$ dB and QPSK, 16, 64 and 256-QAM Modulations.

rate per user and the number of users attended by the system, unfeasible.

However, the use of Walsh spreading sequences with matched filters, brought a significant improvement in the data throughput, which became constant, as a function of the number of users, and crescent, as the QAM modulations order increases. Nevertheless, there is a limitation in terms of the number of users attended by the cell, that is equal to the processing gain. This is due to the fact that the Walsh sequences are orthogonal pairwise, which allows DS-CDMA systems to present interesting characteristics in terms of data throughput. For this, it is necessary that the uplink be synchronous.

It was also shown that the MUD-D detector has overcame the expectations, since its deployment has doubled the data throughput when compared to the case with Walsh spreading sequences and matched filter detection. In this case, the MUD-D detector, as well as the Walsh sequences eliminates the MAI, however, at the expense of increasing the contribution of the background noise. Yet, the noise does not affect excessively the final performance, which has as main point that the number of users employing random sequences can be doubled in relation to the Walsh spreading sequences. However, when considering the presence of external cellular interference, the system presents a large loss of performance due to, mainly, the fact that besides the increased noise, the interfering power is also increased by R_{kk}^{-1}. Nonetheless, this weak performance presented by the MUD-D in the presence of external interference can be increased to get closer to the case with the presence of only one cell, by using some techniques which aims at the mitigation of such type of cellular interferences. Some possibilities are: making use of the cell sectoring technique, antenna array or even increasing the reuse factor.

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