ADAPTIVE PROCEDURE COMBINING ADAPTIVE USER GROUPING AND BIT-LOADING IN A GO-MC-CDMA

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ABSTRACT

Multi Carrier CDMA (MC-CDMA) has shown better results than conventional OFDM systems due to the frequency diversity we achieve with frequency spreading. This spreading is more effective whichever better subcarrier states are found. So the optimal approach should load the subcarriers adaptively according to the subcarriers state. In this paper we investigate the use of adaptive grouped multi-carrier CDMA with adaptive modulation for the downlink with the aim of increasing the system's user-capacity while maintaining a satisfactory BER performance. This scheme allocates the users in their best subcarriers and loads the optimal number of bits per symbols to assure a certain BER.

KEY WORDS

MC-CDMA, user grouping, adaptive modulation, subcarrier allocation

1. Introduction

The first combination between multiple carrier modulation and CDMA scheme have appeared during the nineties more exactly in 1993 under divers transmission forms [1] and up to 1998 big efforts have been made in the optimization detection, decoding, and channel estimation [2]. Despite the different transmission schemes, the Orthogonal Frequency Division Multiplexing (OFDM)-CDMA (Code Division Multiple Access) scheme is one of the most attractive candidates for 4G wireless communication systems and its application rise in many research projects area as in broadband cellular systems (European project MATRICE[1] and 4MORE[2]).

In multipath channels, conventional OFDM (i.e. no spreading sequence is used) without channel state information (CSI) at the transmitter may use channel coding and interleaving across sub-carriers to benefit from frequency diversity. In the case where the OFDM transmitter has channel state information, the loadings can take advantage of good sub-carriers with large amplitude gains and mitigate the negative impact of the spectral nulls [3].

The maximum sum capacity is reached with the multi-user water-filling solution, which allocates to each user a part of the spectrum and requires that the power spectral density (PSD) of each user follow a water-filling distribution. The important conclusion from this generalization of the well-known water-filling solution [4] is that for achieving maximum throughput, the multiple-access scheme should be Frequency Division Multiple Access (FDMA).

In principle MC-CDMA system may also employ adaptive modulation and power loading across user spreading codes. Care must be taken in a multi-user scenario because the base station (BT) experience different channel from each mobile terminal (MT), so the bit carrier allocation that could work for a user does not necessary make sense for other users.

One of the initial schemes for grouping users at the BT appeared in [2] by the use of *Q*-modification in the MC-CDMA system. The intention of the *Q*-modification was to reduce the receiver complexity by reducing the spreading code length per user, while maintaining constant the maximum number of active users and the number of sub-carriers [2][5]. All in all, a special case of the application of the *Q*-modification upon a MC-CDMA system is the Spread Spectrum Multi-carrier Multiple Access (SS-MC-MA) transmission scheme. In SS-MC-MA systems, the code division is used for the simultaneous transmission of the data of one user on the same carrier, whereas in the case of the MC-CDMA systems, the code division is used for the transmission of the data of different users on the same sub-carriers. However, in both schemes the users are grouped only with the purpose of reducing the complexity of the system and no grouping under the channel conditions of the users neither the use of adaptive modulation have been contemplated.

In [6] Al-Susa has developed for a MC-CDMA system a linear programming algorithms that distribute the users in different groups in an adaptive way such that the grouping allows improvement in the quality of service (QoS) in terms of bit error rate (BER) seen by users in the communication system. However, Kim in [7] proposes an algorithm that assigns coefficients to the users. These coefficients mean if that sub-carrier is selected or not, and how much power should be transmitted. Long proposes in [8] a method for assigning the sub-carriers based on the last channel estimation to minimize the BER in Multi-Carrier Direct Sequence CDMA (MC-DS-CDMA).

In spite of that, relatively little investigations have been done in the theme of combining the adaptive grouping of the users at the BS with sub-carrier allocation and adaptive modulation in a downlink MC-CDMA system. The work presented in this proposal combines the

[1] Multicarrier CDMA Transmission Techniques for Integrated Broadband Cellular Systems. European projects IST 2001-32620
[2] European projects 4MORE IST-2002 507039

adaptive grouping of the users based on their effective channel function, and the adaptive modulation using the equivalent sub-carrier principle developed in [9].

Following Introduction, the system model is described in Section II. In Section III, the grouping procedures and the adaptive modulation are developed. The analyses of the system performance are verified in Section IV. Finally, concluding remarks are summarized in Section V.

2. Grouped Orthogonal MC-CDMA system model

In this section two schemes are presented. The ***first transmission scheme*** is an adaptation of the *M&Q – Modification* for the MC-CDMA system [2]. The ***second transmission scheme*** is the adaptive version of the previous scheme.

In both schemes users are splitted into Q groups such that the complexity is kept at a manageable level. Every user has a spreading code $\mathbf{c}^k = [C^k_1\ C^k_2\ ....C^k_L]^T$ ($k=1,...,L$) of length L, and transmit one data symbol over the L carriers that compose each group. Every group block has a maximum user capacity of users $K=L$. The total number of carriers of the system is $N_c=L\times Q$.

The users who are assigned sub-carriers of the same group are separated by a spreading code. In the ***first transmission scheme*** the users have a predefined group location in which they transmit their information, independently of the CSI experienced by each user's group.

After grouping, the data symbol $X_q^{\,k}$ ($k=1,\ldots,K$) of each user k in the q^{th} group is spread by the code $\mathbf{c}^k$. The spread data of all the users of the q^{th} group are then added synchronously at the base station to yield the vector

$$\mathbf{S}_q = \sum_{k=1,k\in G_q}^{K} X_q^k \mathbf{c}^k, \forall\, q=1,\ldots,Q \quad (1)$$

The $\mathbf{S}_q$ signal is modulated using the IFFT and passed through a frequency selective Rayleigh fading channel. The cyclic prefix is assumed greater than the maximum channel delay τ_{max}, and the channel varies slowly compared with the symbol duration. At the receiver (MT *side*) the signal is demodulated using the Fourier transform as,

$$\mathbf{r}^{(k)} = \left[\mathbf{S}_1\ \mathbf{S}_2 \cdots \mathbf{S}_Q\right]^T \times \mathbf{H}^{(k)} + \boldsymbol{\eta}_T \quad (2)$$

where the vector $\mathbf{r}^{(k)} = (R_1^{(k)}\ R_2^{(k)}\ \ldots\ R_{Nc}^{(k)})^T$ is the total signal received at the *k-th* MT. $\mathbf{H}^{(k)} = \mathbf{F}^{-1}\,\mathbf{h}^{(k)}\,\mathbf{F}$ is an ($N_c\times N_c$) matrix, where $\mathbf{F}$ is the Fourier transform matrix.

$$\mathbf{H}^{(k)} = \begin{bmatrix} \mathbf{H}_1^{(k)} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_2^{(k)} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{H}_3^{(k)} & \cdots & \mathbf{0} \\ \vdots & \vdots & \mathbf{0} & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} & \mathbf{H}_Q^{(k)} \end{bmatrix}_{(Q\times Q)} \quad (3)$$

Each element of the diagonal the matrix $\mathbf{H}_q^{(k)}$ is composed by a diagonal matrix, which values are the channel attenuations in the frequency domain,

$$\mathbf{H}_q^{(k)} = \begin{bmatrix} H_{q,1}^{(k)} & 0 & 0 & \cdots & 0 \\ 0 & H_{q,2}^{(k)} & 0 & \cdots & 0 \\ 0 & 0 & H_{q,3}^{(k)} & \cdots & 0 \\ \vdots & \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & H_{q,L}^{(k)} \end{bmatrix}_{(L\times L)} \quad (4)$$

$$\boldsymbol{\eta}_T = \left[\eta_1\ \eta_2 \ldots \eta_L\ \eta_{L+1} \ldots \eta_{N_c}\right]^T \quad (5)$$

and $\boldsymbol{\eta}_T$ represents the additive white Gaussian noise (AWGN) vector of length ($1\times N_c$). Assuming that the receiver (*in the downlink*) has knowledge of the spreading code assigned to each desired user, the symbol detection process is carried out using the zero forcing (ZF) equalization since it restores the orthogonality between the users, then the received signal before de-spreading is,

$$\left[\hat{\mathbf{S}}_1\ \hat{\mathbf{S}}_2 \cdots \hat{\mathbf{S}}_Q\right]^T = \left[\mathbf{S}_1\ \mathbf{S}_2 \cdots \mathbf{S}_Q\right]^T + \frac{\boldsymbol{\eta}_T}{\mathbf{H}^{(k)}} \quad (6)$$

Finally we will obtain the estimated data symbols $\left(\hat{X}_1^{(k)}\ \hat{X}_2^{(k)} \ldots \hat{X}_Q^{(k)}\right)$ of the k-th user by multiplying each vector $\hat{\mathbf{S}}_q, \forall\, q=1,\ldots,Q$ of (6) with the spreading code of the desired user k.

In the ***second transmission scheme,*** represented in Fig.1, users are allocated in groups dynamically. Based on the distinctive channels of the individual users, it is easy to see that the BER performance of the system would greatly improve if those users were adaptively assigned to their best frequency grouping, where they have the best set of sub-carriers, which means the best channel coefficients.

Before assigning each user to its corresponding group, we must consider the length of the groups. Different aspects affect the optimal number of carriers assigned to each group, mainly because the computational cost in the receptor applying Multi-User Detection, is proportional to the number of users in each group. By the way, if the group length (*number of sub-carriers assigned to in each group*) is reduced, we get a loose in frequency diversity, changing from a MC-CDMA system to an OFDM system (*i.e. in the case where each group is constituted by a single carrier*).

The sub-carrier assignment is also another point to consider. In [5] the sub-carriers assigned to each group are separated and equidistant to bring out more frequency diversity. In our proposal, the sub-carriers are consecutive, so the sub-carrier attenuations become similar.

The user grouping can be based on optimizing one of the next three parameters, namely, global power, average bit error rate (BER), and a hybrid of both global power and BER. If the adaptation process is based on optimized the global power, the users and the sub-carriers will be allocated to different groups such that the sum of the power received by all the users in one cell is maximized. On the other hand, whether the adaptation is based on optimizing the BER, the users and the sub-carriers will be allocated that the "*best*" average BER performance across the entire set of users is achieved. Finally the aim of the third criteria is to optimize for global power taking into account the minimum BER per user.

The adaptive grouping proposed in this ***second scheme***, *Adaptive Group Orthogonal* MC-CDMA (AGO-MC-CDMA)**,** attempts to cluster the users into Q groups of length K based on their channel impulse response. In case the number of active users who have to transmit is greater than the maximum allowed (K) per group, a penalisation process occurs and only the K users with the best channel coefficient can transmit in each group.

In this transmission case we assume that the receiver has knowledge of which groups the symbols of the desired user were transmitted, and also which mapping scheme (*constellation size*) has been chosen in each of them. The number of bits assigned to each user's data symbol within every group will be calculated and defined in the next section.

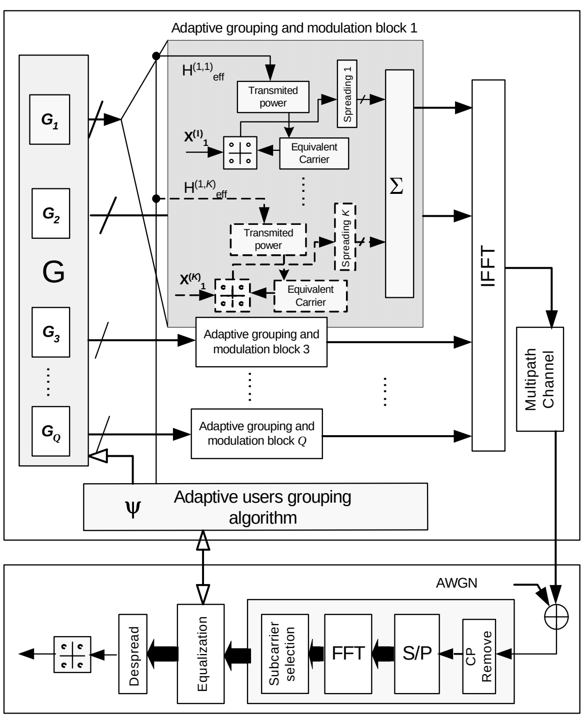

Figure 1: Schematic of GO-MC-CDMA

3. Adaptive modulation procedure

1. EQUIVALENT SUBCARRIER CONCEPT

The Signal to Noise Ratio (*SNR*) is the main parameter we need to resolve in order to know how many bits we can allocate in each sub-carrier assuring a certain BER. Having the *SNR*, we can obtain the best modulation directly from tables that link *SNR* with BER for a fixed mapping scheme, or approximations developed in [10] that determine the maximum number of bits for M-QAM and M-PSK modulations for a given BER bound and the instantaneous SNR. To calculate the *SNR* for the user in each group we will use the equivalent sub-carrier concept introduced in [9].

If we consider a single user case, after spreading with the code $C^{(1)}_l$ for $l=1,\ldots,L$, it becomes a sequence $X^{(1)}C^{(1)}_l$, where the l^{th} element (i.e. chips) of the spreading data symbol is transmitted by the l^{th} sub-carrier. After the demodulation process using the IFFT at the receiver and after the a zero-forcing equalizer then, the received sub-carrier symbol becomes,

$$\frac{Y_l}{H_l} = X^1 C_l^1 + \frac{\eta_l}{H_l} \tag{7}$$

and de-spreading we obtain an estimate $\hat{\boldsymbol{X}}^{(1)}$ of the original data symbol $X^{(1)}$,

$$\hat{X}^{(1)} = X^{(1)} + \frac{1}{L}\sum_{l=1}^{L}\frac{\eta_l}{H_l}C_{1,l} \tag{8}$$

From (7), the enhanced term of noise after equalisation in the l^{th} sub-carrier is given by η_l/H_l. Assuming the noise variance, or power, are identical in all the sub-carriers and let it be σ^2. Then, the power of the enhanced noise term in the l^{th} sub-carrier is $\sigma^2/|H_l|^2$, and after the despreading, the enhanced noise of the de-spreading symbol is given by (8) as $\frac{1}{\boldsymbol{L}}\sum_{l=1}^{\boldsymbol{L}}\frac{\boldsymbol{\eta_l}}{\boldsymbol{H_l}}\boldsymbol{C}_{1,\boldsymbol{l}}$ .Thus the enhanced noise term after de-spreading is,

$$\text{Noise power} = \frac{\sigma^2}{L^2}\sum_{l=1}^{L}\frac{1}{|H_l|^2} \tag{9}$$

After spreading over L sub-carriers, the total transmit power of a single spread data symbol becomes $P=P_s L$, where $P_s = E\{X^*_1 X_1\}$. The effective instantaneous SNR is given by [9],

$$SNR_i = \frac{P}{\sigma^2}\frac{L}{\sum_{l=1}^{L}\frac{1}{|H_l|^2}} \tag{10}$$

The *group* of sub-carriers may be replaced by a *single equivalent* sub-carrier with an effective channel function $|H_{eff}|^2$ as,

$$|\boldsymbol{H}_{\boldsymbol{eff}}|^2 = \frac{\boldsymbol{L}}{\sum_{\boldsymbol{l}=1}^{\boldsymbol{L}}\frac{1}{|\boldsymbol{H_l}|^2}} \tag{11}$$

Thus, the L sub-carriers that compose a specific user in a block group of users may now be interpreted as an equivalent single carrier system. Based on the channel CSI and spreading code assignment for each user in each block group, the base station transmitter can then use this equivalent sub-carrier interpretation in (11) for the purposes of bit and power loading for multiple users operating at the same time.

2. ADAPTIVE MODULATION

Combining (11) and the BER approximation developed in [10] using the l^{th} equivalent single carrier concept we obtain an approximation for the BER as,

$$BER_{MQAM} \approx 0.2 \exp\left(\frac{-1.6 \left| H_{eff} \right|^2 P_i}{\left(2^{b_l} - 1\right)\sigma^2} \right) \quad (12)$$

where $|H_{eff}|^2$ is the square magnitude of the effective channel function, P_i is the instantaneous power and b_l is the number of bits in the l^{th} equivalent sub-carrier channel. Using (10) and (12) the maximum number of bits achieving a fixed BER value is,

$$b_l \approx \left\lfloor \log_2 \left(1 - \frac{1.6 \cdot SNR_l}{\left(\overline{BER}_{l-MQAM} / 0.2\right)} \right) \right\rfloor \quad (13)$$

$\lfloor x \rfloor$ indicates that x is rounded down to the nearest integer. For each of the users, (10) is first invoked to measure the instantaneous SNR, and (13) for assigning bits to each equivalent sub-carrier. The bits are then modulated into symbols, spread and added synchronously with the rest of user's spreading words before transmitting.

3. USER GROUPING, SORTING AND BIT LOADING

In (11) we have an expression of the effective channel coefficients that each user experiences over a set of sub-carriers when transmitting in the system described in Section II. Next steps describe how we can determine which users are preferable to transmit in each group based on CSI.

First, we need the matrix Θ,

$$\Theta = \begin{bmatrix} \frac{1}{\left|H_1^{(1)}\right|^2} & \frac{1}{\left|H_1^{(2)}\right|^2} & \cdots & \frac{1}{\left|H_1^{(U)}\right|^2} \\ \frac{1}{\left|H_2^{(1)}\right|^2} & \frac{1}{\left|H_2^{(2)}\right|^2} & \cdots & \frac{1}{\left|H_2^{(U)}\right|^2} \\ \vdots & \vdots & & \vdots \\ \frac{1}{\left|H_{N_c}^{(1)}\right|^2} & \frac{1}{\left|H_{N_c}^{(2)}\right|^2} & \cdots & \frac{1}{\left|H_{N_c}^{(U)}\right|^2} \end{bmatrix}_{Nc \times U} \quad (14)$$

This matrix contains all the users inverse channel coefficients. U is the number of active users.

The next matrix **B** indicates how the sub-carriers are distributed to each group. Each column represents each group, and we will place ones in those sub-carriers that have been assigned to that group, taking care of not assigning the same sub-carrier to more than one group. As it was indicated earlier, the sub-carriers assigned are consecutive, thus $\mathbf{b_q}$ is a vector of ones with length K.

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}_1 & 0 & \cdots & 0 \\ 0 & \mathbf{b}_2 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \mathbf{b}_Q \end{bmatrix}_{Nsc \times Q} \quad (15)$$

The next step consists on calculating the system effective channel matrix Ψ,

$$\Psi = L \cdot \left(\Theta^T \times \mathrm{B} \right)^{(-1)} = \begin{bmatrix} Heff_{1,1} & Heff_{1,2} & \cdots & Heff_{1,Q} \\ Heff_{2,1} & Heff_{2,2} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ Heff_{U,1} & \cdots & Heff_{U,Q-1} & Heff_{U,Q} \end{bmatrix} \quad (16)$$

.

$(.)^{(-1)}$ means the element by element inverse, and × denotes the matrix multiplication. The dimension of Ψ is U×Q, and each element represents the effective channel coefficient experienced by each user in every group. Now sorting Ψ in group direction (column-wise), the coefficients of the best users will be placed in the top positions (for descending sorting). The K best users will be allowed to transmit in that group. It can be observed that with this procedure we are solving (11) for all the users in each group with few simple operations. Finally we will assign the best modulation scheme using (10) and (13).

Note that whether a user suffers a deep fading in any sub-carrier from a certain group, the probability to be assigned to that group is very low unless the system is not occupied by others users (*in the case where U is lower than K*).

4. Simulations Results

Simulations have been done in a multi-user, single cell scenario to verify the proposed adaptive scheme. The parameters simulations can be found in Table I and are considered possible values for a 4G mobile cellular system [11].

In figure (2), we represent the improvement achieved incrementing the number of active users (U) for a fixed modulation with the transmission scheme presented in Section II. In fact, each time we increase the number of users we are giving more diversity to the system. In the case that U=K the system implemented is equivalent to the *M&Q-modification*. For figure (3), the effects of changing the spreading factor are studied. As a conclusion, it can be observed that when U=L^2 the results get close to the AWGN channel for these test conditions.

In figure (4) channel efficiency is studied using the developed grouping algorithm and adaptive modulation technique. The used mapping schemes is M-QAM with M={0, 2, 4, 16, 64, 256}, the 0-QAM represents the case that user can not transmit because the fixed BER can not be guaranteed. If we compare the results of this proposal to the results achieved by the GMC-CDMA system (equivalent to the case $U=L$) we can observe that it could be possible to transmit up to one bit more per symbol when $U=2L$, and up to two bits more when $U=L^2$.

From the obtained results, it can be conclude that it is possible to transmit up to one bit more per symbol when transmitting at double of the normal system capacity, and up to two bits more with eight times the user capacity. Obviously each time the number of active users is increased, the average transmitted bits per user decreases. Otherwise the overall system capacity (*bits transmitted by the BS*) also increases, this can be observed in the values depicted in Table II. We can note also from Table II, that the percentage of user's transmitted bits with respect to the total transmitted bits is quite different from those users who experiences better channel conditions to those that suffers worse. This causes that we can not ensure a minimum throughput per user, as usually it depends on the user channel state and also in the other users channel state. In figure (5) we appreciate how the BER never over goes the fixed BER threshold (*in this case* BER<10^{-3}).

Finally, figure (6) shown the effects of the channel estimation developed in Section III, and several mobility parameters are considered. The channel estimation is taken from the pilot carriers transmitted in the last OFDM symbol during the UL frames. Thus the channel estimation process in every sub-carrier is taken almost at the beginning of each the DL transmission mode. It is observed that the system performance is degraded as velocity increases since the channel parameters varies faster, therefore the grouping process becomes in this case less effective. It is important to notice that in case the channel conditions varies so fast, the grouping selection does not produce any benefit from point of view of the system performance, the obtained results are similar to the case when the grouping has not been done, but the performances will never be worse.

5. Conclusions

Adaptive Group Orthogonal with adaptive modulation for MC-CDMA systems was shown to produce a significant spectral efficiency and QoS improvement. But the scheme presented here has the disadvantage that it can not guarantee an instantaneous throughput to a user, this would not be a problem for data networks but some changes should make to assure a minimum throughput. These changes should assign at least one group to those users that require transmitting despite the channel state, and also the scheme should limit the maximum instantaneous throughput to avoid channel monopolisation from users that experience a very good channel state. It is remarkable that for grouping and bit loading, equivalent sub-carrier and effective channel concept developed by Tang has produced great results, and the proposed scheme has brought a computational efficient method to resolve the grouping and bit loading problem in few steps. Finally the number of carriers in each group should be more deeply analysed to find out which spreading factor performs better in each case.

PARAMETER	VALUE
Transmission mode	Down-Link TDD mode
Frequency Carrier	5 GHz
Number of Carriers	$N_c = 1024$
Sampling Frequency	57.6 MHz
Modulation	M-QAM {0,2,4,16,64,256}
Multipath Channel Model	BRAN channel E, Perfect Estimation
MT Velocity	10 Km/h
Cyclic Prefix Time	3.75µs
UL/DL Guard Time	20.83 µs
Slot Time	0.667 mseg
Spreading type and Factor	Walsh-Hadamard , *L*=8
Equalization type	Zero Forcing

Table I – Default simulation parameters

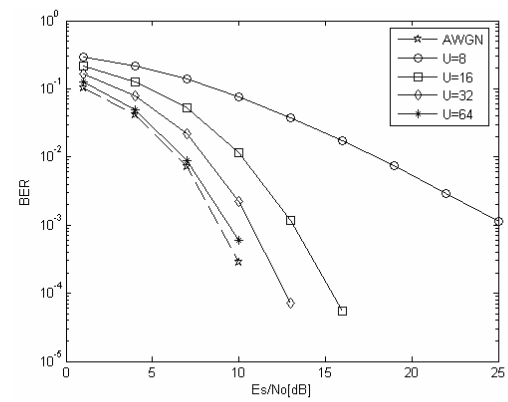

Figure 2: BER versus Es/No with a fixed 4-QAM modulation and different number of active users (*U*)

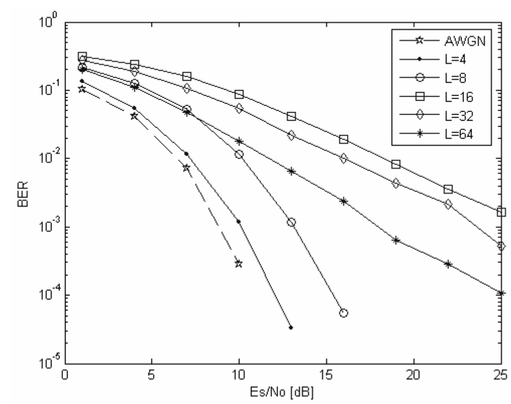

Figure 3: BER versus Es/No with a fixed 4-QAM modulation and different spreading factors (L) and *U*=16

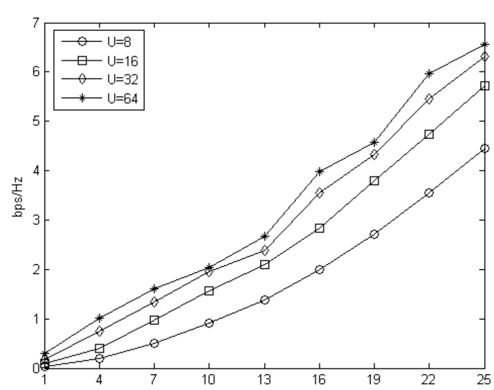

Figure 4: Spectral efficiency for Adaptive Grouping and Modulation (A-G&M) and different *U* for a BER<10^{-3}

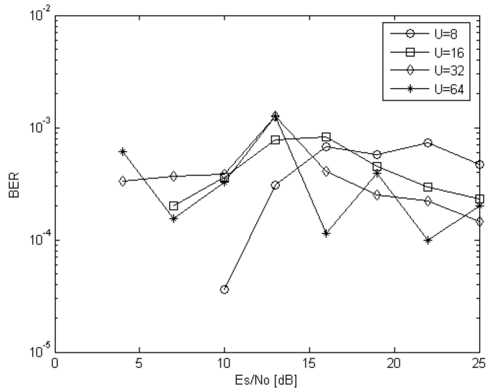

Figure 5: BER versus Es/No [dB] for A-G&M and different number of active users for a BER bound $<10^{-3}$

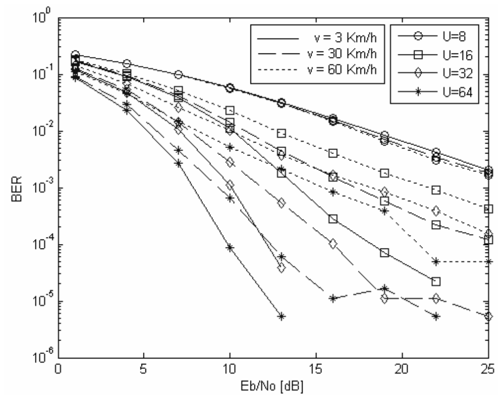

Figure 6: BER versus Es/No for A-G&M, fixed 4-QAM and different *U* at TM velocities v={3,30,60} with non-perfect channel estimation

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