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Research Article

How Equalization Techniques Affect the TCP Performance of MC-CDMA Systems in Correlated Fading Channels

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This paper investigates the impact of several equalization techniques for multicarrier code division multiple access systems on the performance at both lower and upper layers (i.e., physical and TCP layers). Classical techniques such as maximal ratio combining, equal gain combining, orthogonality restoring combining, minimum mean square error, as well as a partial equalization (PE) are investigated in time- and frequency-correlated fading channels with various numbers of interferers. Their impact on the performance at upper level is then studied. The results are obtained through an integrated simulation platform carefully reproducing all main aspects affecting the quality of service perceived by the final user, allowing an investigation of the real gain produced by signal processing techniques at TCP level.

1. INTRODUCTION

Multicarrier code division multiple access (MC-CDMA) techniques have achieved considerable attention and, owing to their efficiency in counteracting both multiuser interference and frequency selective fading, are also proposed for fourth generation mobile radio systems (see, e.g., [1–5]). Several MC-CDMA schemes have been proposed in the literature (an overview on MC-CDMA systems can be found in [6]) and different variants can be derived from them. In this work, we investigate the downlink performance, in realistic channel conditions, of the MC-CDMA system presented in [1, 7]. For what concerns the equalization and combining techniques, several solutions are here considered with the aim of evaluating their impact at upper layers through an integrated approach which takes into account all aspects affecting the performance perceived by the final user, from physical to application level [8].

In particular, the MC-CDMA scheme here considered performs the signal spreading in the frequency-domain, thus resulting in a combination of orthogonal frequency division multiplexing OFDM and CDMA techniques, and adopts orthogonal Walsh-Hadamard (W-H) spreading sequences with spreading factor equal to the number of subcarriers for the receiver block schemes). However, in spite of the use of W-H codes, the orthogonality of the sequences of different users is lost due to the different fading in each subchannel [4]. Therefore, in order to improve the system performance, the choice of the combining technique is a crucial point.

Many combining solutions have been studied in the literature; in this work, we focus on linear combining techniques representing low complexity solutions, as requested for mobile terminals implementation. Within the family of linear combining techniques, equal gain combining (EGC), maximum ratio combining (MRC), orthogonality restoring combining (ORC) (ORC is also known as zero forcing (ZF)), and threshold ORC (TORC) have been deeply investigated in the literature (see, e.g., [6, 7]). It is well known, in fact, that MRC represents the best choice when the system is noise-limited because it combines with the higher weights the subchannels contributions with the higher signal-to-noise ratio (SNR); on the contrary, when the system is interference-limited, ORC can be employed to cancel multiuser interference, with the side effect of enhancing the noise. For this reason, a threshold is introduced with TORC (see, e.g., [9]) to cancel the contributions of those subchannels highly corrupted by the noise [10]. Among linear combining techniques, the optimum solution is represented by minimum mean square error (MMSE) (see, e.g., [11]), but it also requires the knowledge of the SNR and the number of active users, increasing the receiver's complexity. A suboptimal MMSE solution has been, therefore, proposed which reduces the burden of MMSE implementation [4].

In addition to the above mentioned techniques, in this paper, we also consider a promising partial equalization (PE) technique investigated in [12]. In uncorrelated fading channels its performance is analytically tractable: PE has a mean bit-error probability (BEP) averaged over fast fading close to the optimum MMSE, despite having the same complexity of EGC, MRC, ORC, and TORC.

The novelty of this work consists in evaluating the effect of the above-mentioned physical level combining techniques not only on the bit-error rate (BER), but also at TCP level in terms of normalized throughput (whose definition will be given in Section 6), thus providing an insight on the performance experienced by the final user. Moreover, realistic channel conditions with correlation in both frequency and time are considered here. In fact, in the literature (see, e.g., [13–16]), the effects of the equalization techniques are essentially investigated at the physical level (typically on the BER), without considering the upper levels performance. If the upper layers protocols are without memory, the effect of physical level equalization techniques on the throughput would directly be related to those on the BER. Since the TCP protocol is widely affected by the memory effect produced by the channel correlation, hence, this does not a priori allow to assert what is the effect of the combining techniques on the throughput. These considerations suggested us to carefully investigate, in this paper, how equalization techniques play on the TCP throughput.

Moreover, let us emphasize that in order to derive meaningful results, the TCP level performance has been derived through a complete investigation which carefully takes into account all main aspects affecting the throughput perceived by the final user, such as channel characteristics, modulation and coding schemes, Automatic Repeat reQuest (ARQ) strategy, TCP behavior, and so forth. A simulative approach has been adopted since it is the only feasible way to take all the above mentioned aspects into account.

To summarize, the goals of the paper are

(i) to understand how equalization techniques affect the performance at upper layers in realistic conditions;
(ii) to compare several equalization techniques not only in terms of physical level performance but also at TCP level;
(iii) to verify which technique is more suitable to serve different amount of users in realistic channel conditions;
(iv) to maturate the feeling on the presence or absence of general rules on equalization techniques in different conditions for a given target TCP performance.

The paper is organized as follows: in Section 2, modelling and assumptions for the investigated MC-CDMA system are detailed, and in Section 3 an overview of equalization techniques is provided. In Sections 4 and 5, the adopted simulation platform and its configuration are discussed. In Section 6, the numerical results are provided and, finally, in Section 7, the final conclusions are drawn.

2. MODELLING AND ASSUMPTIONS AT PHY LEVEL

Following the MC-CDMA architecture in [6], the number of subcarriers, M, is equal to the spreading factor. Each data-symbol is copied over all subcarriers, and multiplied by the chip assigned to each particular subcarrier. Consequently, the spreading is performed in the frequency-domain. In the following we will focus our attention on the downlink of an MC-CDMA system with the commonly accepted assumptions such as the system remains always synchronous, and possible different delays affecting each subcarriers are assumed to be perfectly compensated (see, e.g., [1, 7, 17]).

We consider W-H orthogonal code sequences for the multiple access and binary phase shift keying (BPSK) modulation. Considering that, exploiting the orthogonality of the code, all the different users use the same carriers, the total transmitted signal results in (being in the downlink, the phase is the same for all the values of m, thus assumed zero for simplicity)

$$s(t) = \sum_{m=0}^{M-1} \sum_{i=-\infty}^{+\infty} A_m[i] g(t - iT_b) \cos(2\pi f_m t), \qquad (1)$$

being

$$A_m[i] = \sqrt{\frac{E_b}{M}} \sum_{k=0}^{N_u-1} c_m^{(k)} a^{(k)}[i], \qquad (2)$$

where m is the subcarrier index, i denotes the data index, $g(t)$ is a rectangular pulse waveform, with duration $[0, T]$ and unitary energy, T_b is the bit-time, $f_m = f_0 + m\cdot\Delta f$ is the subcarrier frequency (with $\Delta f \cdot T$ and $f_0 T$ integers to have orthogonal frequencies), E_b is the energy per bit, M is the number of subcarriers, N_u is the number of active users and, because of the use of orthogonal codes, $N_u \le M$, c_m is the mth chip (taking value ± 1): and $a^{(k)}[i]$ is the data-symbol transmitted during the ith time-symbol. We assume orthogonal sequences $\overline{c^{(k)}}$ for different users, such that

$$\left\langle \overline{c^{(k)}}, \overline{c^{(k')}} \right\rangle = \sum_{m=0}^{M-1} c_m^{(k)} c_m^{(k')} = \begin{cases} M & k = k', \\ 0 & k \neq k'. \end{cases} \qquad (3)$$

In particular, $T_b = T + T_g$ is the total OFDM symbol duration, increased with respect to T of a time-guard T_g inserted between consecutive multicarrier symbols to eliminate the residual intersymbol interference (ISI) due to the channel delay spread and the inter carrier interference.

As far as the channel model is concerned, we consider two cases:

(i) uncorrelated Rayleigh fading on each subcarrier;
(ii) time and frequency correlated fading channels.

Table 1: Three rays SUI channels models: delays, attenuations, and K Ricean factor ($K = 0$ means Rayleigh distribution).

SUI-1	Tap1	Tap2	Tap3
Delay [μs]	0	0.4	0.9
Attenuation [dB]	0	15	20
K	4	0	0
SUI-2	Tap1	Tap2	Tap3
Delay [μs]	0	0.4	1.1
Attenuation [dB]	0	12	15
K	2	0	0

Table 2: Rayleigh three paths (R3P) channels models: delays and attenuations.

R3P-A	Tap1	Tap2	Tap3
Delay [μs]	0	0.4	1.1
Attenuation [dB]	0	12	15
R3P-B	Tap1	Tap2	Tap3
Delay [μs]	0	0.4	1.1
Attenuation [dB]	0	8	12
R3P-C	Tap1	Tap2	Tap3
Delay [μs]	0	0.2	0.8
Attenuation [dB]	0	12	15
R3P-D	Tap1	Tap2	Tap3
Delay [μs]	0	0.2	0.8
Attenuation [dB]	0	8	12

The assumption of uncorrelated fading among subcarriers represents the situation when the subcarriers are sufficiently spaced in frequency (i.e., more than the coherence bandwidth) or when only a sparse subset of the total amount of subcarriers is used for a symbol transmission.

In the case of correlated fading channels,

(i) the SUI three-rays channel models [18] (adopted, e.g., for WiMAX system)
(ii) the Rayleigh three paths (R3P) channel models

have been assumed in the 2 GHz band as summarized in Tables 1 and 2, respectively.

Since we are now focusing on the downlink, we assume that considering the nth receiver, the information associated to different users experiments the same fading. Due to the CDMA structure of the system, each user receives the information of all the users and selects only its own data through the spreading sequence. The received signal can be written as

$$r(t) = s(t) * h(t) + n(t), \tag{4}$$

where operator $*$ here denotes the convolution operation, $h(t)$ is the impulse response of the channel, and $n(t)$ is the additive white Gaussian noise with two-side power spectral density (PSD) $N_0/2$.

Hence, by denoting with H_m the channel gain for the mth subcarrier, the mth signal at the FFT output can be written as

$$z_m[i] = H_m[i]A_m[i] + n_m[i]. \tag{5}$$

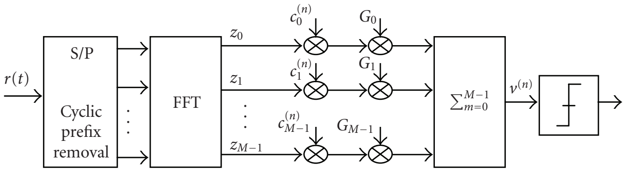


Figure 1: Receiver block-scheme for the nth user.

To be rigorous, $z_m[i] = \delta_d \cdot H_m[i]A_m[i] + n_m[i]$, where $\delta_d = 1/(1 + T_d/T)$ represents the loss of energy caused by the time-spreading of the impulse. Since $\delta_d \simeq 1$, we will neglect it in the following. Focusing, without loss of generality, on the nth user, the decision variable (i.e., the test statistic), $v^{(n)}[i]$, is obtained by linearly combining the weighted signals from each subcarrier as follows (see Figure 1):

$$v^{(n)}[i] = \sum_{m=0}^{M-1} z_m[i] G_m c_m^{(n)}, \tag{6}$$

being G_m the mth channel weight, which has to be properly chosen according to the equalization strategy. Its impact on the performance at both physical and TCP level is investigated.

3. EQUALIZATION TECHNIQUES FOR MC-CDMA SYSTEMS

Within the family of linear combining techniques, different schemes based on the channel state information are known in the literature (see, e.g., [19]), where signals coming from different subcarriers are weighted by suitable coefficients G_m.

The EGC technique, for instance, consists in equally weighting each subchannel contribution and compensating only the phases, as in

$$G_m = \frac{H_m^*}{|H_m|}, \tag{7}$$

where operation $*$ stands for complex conjugate.

As investigated in [1], if the number of active users is negligible with respect to the number of subcarriers, that is, the system is noise-limited, the best choice is represented by a combination in which subchannels with the higher SNRs have the higher weights, as in the MRC, where

$$G_m = H_m^*. \tag{8}$$

On the other hand, this choice totally destroys the orthogonality among the codes. For this reason, if the number of active users is high (the system is interference-limited), a good choice is given by restoring at the receiver the orthogonality among the sequences. This means to cancel the effects of the channel on the sequences as in ORC, where

$$G_m = \frac{1}{H_m}. \tag{9}$$

This implies a total cancellation of the multiuser interference, but, on the other hand, this method enhances the noise, because the subchannels with low SNRs have higher weights.

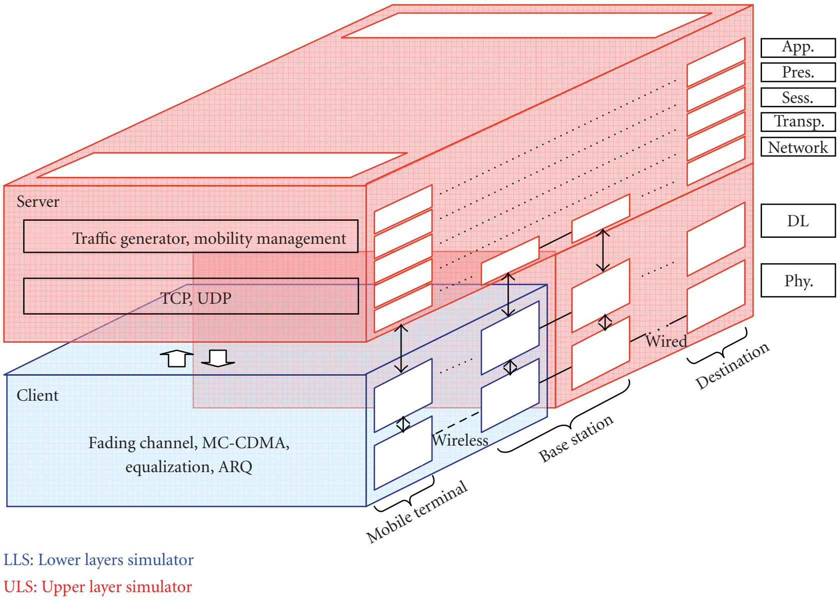


Figure 2: Simulation platform architecture.

In [1] it is shown that in a Rayleigh fading channel, this technique raises the noise contribution to infinity (i.e., $\mathbb{E}\{|H_m|^{-2}\}$ approaches infinity, where $\mathbb{E}\{\cdot\}$ represents the statistical expectation). Consequently, a correction on G_m is introduced in [10], as follows:

$$G_m = u(|H_m| - \rho_{\text{TH}})\frac{1}{H_m}, \tag{10}$$

where $u(\cdot)$ is the unitary-step function and the threshold ρ_{TH} is introduced to cancel the contributions of subchannels highly corrupted by the noise. This method is the so-called controlled equalization (CE) or TORC technique.

However, exception made for the two opposite cases of one active user in the presence of noise (giving MRC as the best solution) and multiple users with negligible noise (giving ORC), none of the presented methods represents the optimum solution for real cases of interest.

Still considering simple equalization techniques, here we also investigate the PE strategy presented in [12], where coefficients G_m depend on a parameter β as in the following:

$$G_m = \frac{H_m^*}{|H_m|^{1+\beta}}. \tag{11}$$

Note that (7), (8), (9) can be viewed as particular cases of (11) for which the parameter β assumes the values 0 (EGC), -1 (MRC) and 1 (ORC), respectively. The key idea is that since MRC and ORC are optimum in the extreme cases of noise-limited and interference-limited systems, respectively, for each intermediate situation there should exist an optimum value of the parameter β which minimizes the mean BEP averaged over fast fading.

For linear equalization, the optimum solution is the well-known MMSE technique, whose coefficient expression is given by

$$G_m = \frac{H_m^*}{|H_m|^2 + 1/N_u\overline{\gamma}}, \tag{12}$$

where N_u is the number of active users and $\overline{\gamma}$ is the mean SNR averaged over fast fading. However, while the previously mentioned techniques are only based on the channel state information, MMSE has the additional complexity to obtain information about the SNR and the number of active users, thus representing a more complex solution, especially in the downlink where the computation is done in the mobile unit. For this reason a suboptimal MMSE technique was presented in [4], where the term $1/(\overline{\gamma}N_u)$ in (12) is replaced by the coefficient λ:

$$\lambda = \frac{1}{\overline{\gamma}_{\max}\cdot M}, \tag{13}$$

where $\overline{\gamma}_{\max}$ is the maximum allowable SNR to achieve a maximum acceptable BEP in fully loaded conditions and M is the number of subcarriers (M is equal to the spreading factor, thus $N_u = M$ is the full user capacity).

More complex nonlinear equalizers, such as the maximum likelihood detection (MLD) and iterative detection, attain better performance [4]. However, in many cases, such as in mobile radio scenarios, the computation is done in the mobile unit and it is fundamental to have a detection scheme capable to attain good performance with low complexity. For these reasons, in this work, we will focus on linear equalization techniques.

Hence, by substituting, for instance, (11) (which is quite general including different combining techniques varying the value of the parameter β) in (6), the decision variable becomes

$$\begin{aligned} v^{(n)} =& \overbrace{\sqrt{\frac{E_b\delta_d}{M}}\sum_{m=0}^{M-1}\left|H_m\right|^{1-\beta}a^{(n)}}^{U} + \overbrace{\sum_{m=0}^{M-1}\left|H_m\right|^{-\beta}n_m}^{N} \\ &+ \overbrace{\sqrt{\frac{E_b\delta_d}{M}}\sum_{m=0}^{M-1}\sum_{k=0,\,k\neq n}^{N_u-1}\left|H_m\right|^{1-\beta}c_m^{(n)}c_m^{(k)}a^{(k)}}^{I}, \end{aligned} \tag{14}$$

where U, N, and I are the useful, noise, and interference term, respectively. In the same way, the decision variable for TORC, MMSE, and suboptimum MMSE techniques can be obtained.

In order to derive the numerical result presented in Section 6, the value of the decision variable is assessed for each transmitted symbol during the simulation and the decision on the correct/erroneous reception of symbols is taken by comparing it with the threshold 0 (let us recall that we are considering a BPSK modulation scheme).

4. THE SIMULATION TOOL

In order to investigate the impact of PE on TCP level performance, we realized an accurate MC-CDMA physical level simulator, carefully reproducing all modulation and equalization aspects, and then we integrated it in our simulation platform SHINE simulation platform for heterogeneous interworking networks [20] which, as detailed in the following, allows to reproduce the behavior of the entire protocol pillar of a communication system, from physical to application level.

SHINE was developed, in particular, with the objective to reproduce the behavior of wireless access-networks (3G, 4G, WLAN, WiMAX, etc.), taking care of all aspects related to every single protocol level affecting the achieved performance.

In order to have a complete picture of the methodology adopted to derive the numerical results provided in Section 6, further details on SHINE are given in the following.

4.1. *SHINE architecture.*

The SHINE simulation platform has been realized according to a client-server structure and is constituted, in particular, by one server-core simulator hereafter called upper layers simulator (ULS) and one or more client simulators lower layers simulators (LLSs), specific for the considered access technologies (see Figure 2 where, for the sake of clarity, only one LLS is depicted).

The ULS simulator is, in its turn, constituted by an access network(s) side and a core network side: at the access network(s) side the ULS takes care of all information related to those users operating within the region covered by the simulated access-networks, such as their mobility, class of service, and so forth and of the end-to-end aspects of each connection, such as the generation of the application-level traffic and the users' TCP or UDP dynamics; at the core-network side, instead, the ULS takes care of all aspects concerning communications.

Focusing the attention on the access network(s) side, it is worth noting that the ULS structure, being related to the end-to-end aspects of communications, is independent on the particular access technology (WLAN, 3G, 4G, etc.) adopted to establish the user connection.

All aspects related to the access technologies adopted, hence related to the data-link and physical layers, are managed by LLSs, which are the client simulators and are specific for each access technology, so that our simulation platform provides the presence of so many LLSs as technologies adopted in the investigated scenario (see Figure 2).

For the purpose of the investigation described in this paper, we realized an "ad hoc" LLS which reproduces the behavior of an MC-CDMA physical level, and, as far as the data link level is concerned, the medium access control (MAC), ARQ, and duplexing strategies detailed in the following section.

What is really remarkable about SHINE is that ULS and LLSs are distinct executables; nonetheless the ULS communicates run time with the LLS through the TCP sockets of the computer operating-system, thus simulating vertical communications among the protocol layers.

4.2. *ULS and LLSs main tasks*

As previously stated, the ULS manages the end-to-end aspects of each connection (no matter the access technology supporting it at the physical and data-link levels), hence its tasks are mainly concerned with communications management (connections setup and closure, management of application level traffic flows, etc.), the simulation of transport level protocols (TCP, UDP, etc.) and the processing of simulation outcomes to provide application level performance. In particular, the main tasks of ULS are

(i) to set the starting instant of each new traffic session originated by users according to the arrival statistics of the traffic class it belongs to (http, e-mail, voice calls, etc.), as well as users positions within the investigated scenario;
(ii) to manage connection setup and closure procedures;
(iii) to generate the bit-flows up(down)loaded by users in each session according to the statistics of their class of traffic;
(iv) to reproduce the transport protocol behavior;
(v) to perform packet segmentation and reassembly;
(vi) to collect, finally, all simulation outcomes and to generate the outputs (user satisfaction rate, throughput, packet delivery delays, etc.) from an end-to-end point of view.

As for the LLSs, since they are specific for the particular access technologies investigated, their tasks are mainly concerned with data-link and physical level aspects of communications and, in particular, are

(i) to perform, if required, the call admission control specific of the technology it simulates and all technology specific radio resource management actions;
(ii) to manage, if required, the transmission scheduling at the data-link level level;
(iii) to perform MAC or RLC fragmentation and reassembly of TCP-IP level packets;
(iv) to simulate MAC/RLC behavior of the given technology;
(v) to reproduce all physical level procedures related to each transmission and reception: power control, handover, radio frequency measurements, channel coding, modulation, information detection, decoding, and so forth;
(vi) to collect, finally, all simulation outcomes and to generate the outputs (user satisfaction rate, throughput, packet delivery delays, etc.) from the wireless links point of view (i.e., at data-link and physical levels).

The specific configuration of the simulation platform adopted for the present investigation is detailed in the following section.

5. LLS AND ULS ASSUMPTIONS

ULS assumptions

Since our investigation is focused on the impact of physical level phenomena (interference, equalization technique, etc.) on TCP performance, the ULS does not implement any routing strategy, whose investigation is outside the scope of this paper. The transport level has been, on the contrary, accurately simulated, since its behavior is very sensitive to the reliability of communications; all aspects of slow-but-steady variant of TCP New Reno [21], in particular, have been implemented.

Finally, the simulated application level traffic reproduced heavy traffic conditions, corresponding to a huge file transfer (FTP session) saturating the downlink communication capacity.

Section 6, the quality of service perceived by the final user is investigated in terms of normalized TCP level throughput. This performance figure is defined as the average amount of TCP level data bits that is correctly received in one second, normalized to its maximum value (achieved when no transmission error occurs). Please remind that, before transmission over the wireless channel, TCP data bits are added of TCP and IP overheads, fragmented, added of RLC-MAC overheads, coded and finally modulated; all these passages are carefully reproduced in our simulator.

LLS assumptions

As previously illustrated, LLS should simulate the behavior at physical and data-link levels of the investigated system. It follows that we had to simulate not only an MC-CDMA receiver with different equalization techniques, which are strictly physical level aspects, but also data link aspects, such as the MAC and ARQ strategies as well as the duplexing scheme.

As far as channel coding technique is concerned, we adopted a 1/2 rate convolutional code with 64 states, polynomial generators (133,171) in octal and hard decision. Moreover, we consider an interleaving process with depth equal to the codeword length (12 byte in the present work).

As for the MAC strategy, its implementation is intrinsic in the nature of MC-CDMA signals, which allow multiple users to transmit in the same frequency and time domains by simply exploiting the orthogonality of spreading codes.

As far as the ARQ strategy is concerned, the following mechanism has been implemented in the LLS:

(i) a cumulative ACK is periodically sent to the transmitter when no transmission error is detected;
(ii) a selective negative ACK is sent as soon as a transmission error is detected.

Finally, with reference to the duplexing technique, we implemented the time division duplexing (TDD) scheme. To accommodate asymmetric traffic flows in the two directions, we assumed a 7/3 downlink/uplink duration ratio and 10 milliseconds of total frame duration.

6. NUMERICAL RESULTS

In this section, the performance at both physical and TCP levels for the downlink of the above described MC-CDMA system is investigated. Different conditions in terms of combining technique, propagation channel, number of interferers, and SNR are considered.

As far as the system parameters are concerned, a total bandwidth of 14 MHz with $M = 64$ equally spaced subcarriers has been considered, with symbol time $T_b = 4.57\,\mu$microseconds, and guard time $T_g = T/4$, thus greater than the highest delay of the channel models.

In the two directions, we assume asymmetric traffic flows with downlink/uplink duration ratio equal to 7/3, a total frame duration of 10 milliseconds and ideal uplink. Thus, it is immediate to verify that in this scenario the downlink maximum available throughput at TCP level results to be 55.4 Kbps per each user. Since we are interested in understanding how physical level impacts the TCP throughput despite its maximum value, which depends on system parameters, in the following the achieved throughput will be normalized to the maximum available and presented in percentage.

In Figure 3, physical level performance is reported in uncorrelated Rayleigh fading channel. The BER at the decoder input for PE with $\beta = 0.5$ and MRC (i.e., $\beta = -1$) as a function of the SNR (dB) for different numbers of interferers can be observed. Regarding the PE, the value $\beta = 0.5$ has been considered since it is close to the one providing the optimum performance in uncorrelated Rayleigh channel conditions as shown in [12]. Simulation results have been compared with analytical curves obtained following the methodology proposed in [12] with very good agreement. This also confirms the accuracy of our simulator in capturing physical effects such as multipath propagation, noise, interference, modulation, and equalization. Figure 3 also allows to verify that MRC represents the optimal solution in the absence

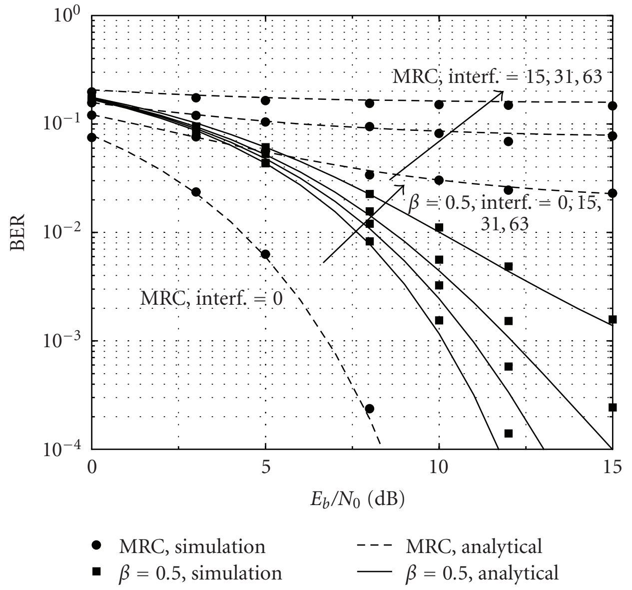
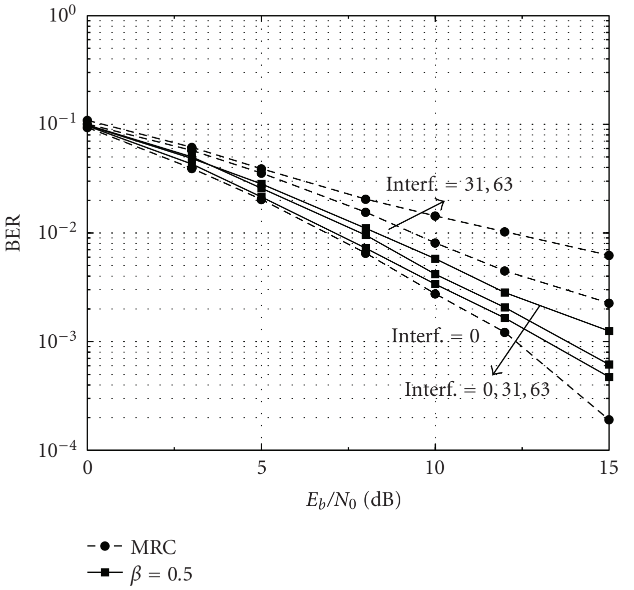
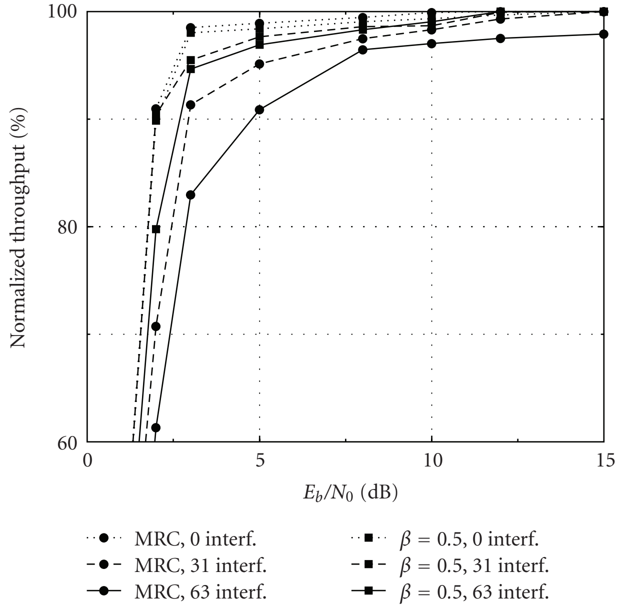


FIGURE 3: BER versus E_b/N_0 (dB) for partial equalization with $\beta = -1$ (MRC) and $\beta = 0.5$ when varying the number of interferers in uncorrelated Rayleigh fading channels. Analytical and simulation results are compared.



(a) BER versus E_b/N_0 (dB)



(b) Normalized throughput versus E_b/N_0 (dB)

FIGURE 4: BER and normalized throughput versus E_b/N_0 (dB) for $\beta = -1$ (MRC) and $\beta = 0.5$ and for different number of interferers. Time and frequency correlated SUI-1 channel.

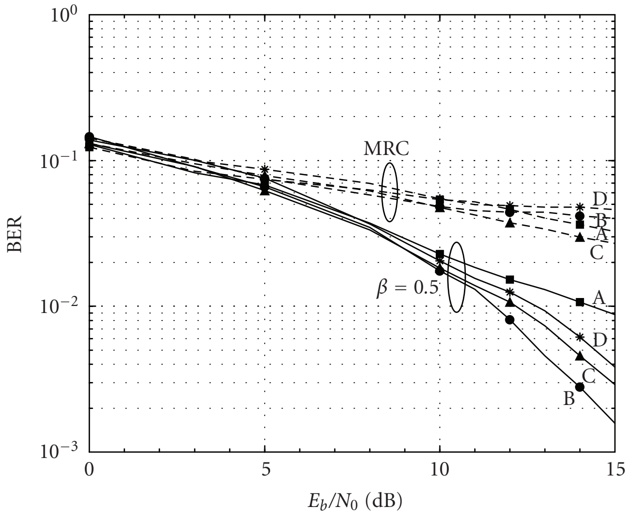
of interference. As the number of interferers increases (note that MC-CDMA systems are usually considered for highly interfered conditions), the performance becomes significantly worst. On the other hand, PE with $\beta = 0.5$ significantly improves the performance as the interference increases with respect to MRC and makes the system less sensitive to the number of interferers. In fact, as an example result, in the case of 15 interferers (i.e., with a system load of 25%), the case $\beta = 0.5$ outperforms MRC already with 15 interferers.

It is now interesting to understand how these behaviors are confirmed also in time and frequency correlated fading channels, such as in SUI-1. In Figure 4, the impact of equalization techniques at both physical and TCP levels is investigated in SUI-1 channel model. Here, the normalized TCP throughput is reported as a function of E_b/N_0 in dB as well as of the number of interferers and of the equalization techniques ($\beta = -1$ and $\beta = 0.5$ are considered).

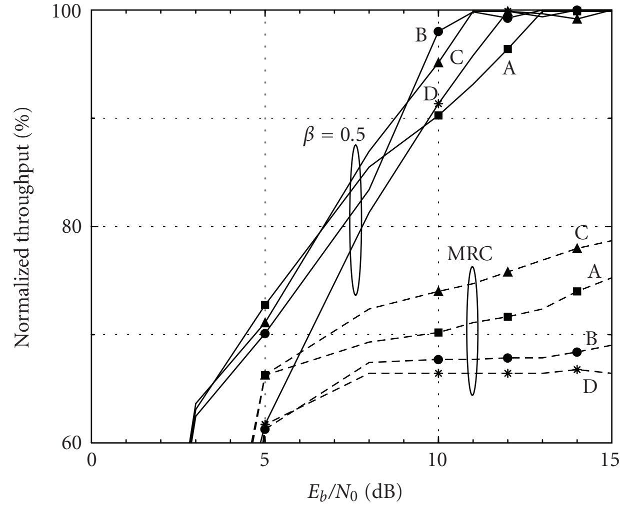
As can be observed, considerations similar to those made for Figure 3 in uncorrelated channel can be made for Figure 4(a). Also in this case the impact of the combining technique and the number of interferers can be clearly observed. Moreover, all considerations suggested by Figure 4(a) with reference to the physical level are confirmed also at TCP level (see Figure 4(b)). It is noticeable that the limited sensitivity of the performance to the number of interferers given by PE with $\beta = 0.5$ is even more evident at TCP level. Moreover, the adoption of a particular equalization technique, such as PE in this case, at physical level can result in relevant throughput gain for several system loads at low SNRs, whereas the impact at the TCP level of the combining technique is less evident when the SNR increases. Note that the performance at TCP level for uncorrelated Rayleigh channel is not investigated due to the TCP characteristic of being particularly sensitive to correlated events.

This is an example on how our framework enables the careful verification of the impact of physical level solutions on the TCP performance.

In Figure 5, the BER and normalized throughput as a function of E_b/N_0 (dB) are shown in different types of correlated R3P channel models (see Table 2 for details), in fully loaded conditions ($N_u = M = 64$). The advantage of using

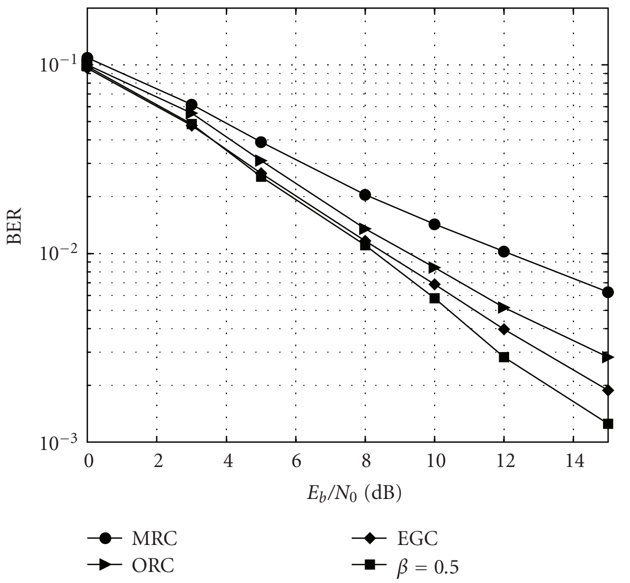


(a) BER versus E_b/N_0 (dB)

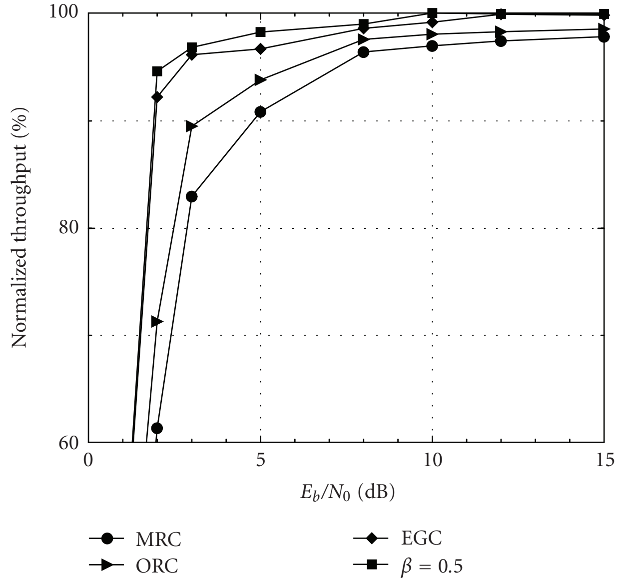


(b) Normalized throughput versus E_b/N_0 (dB)

FIGURE 5: BER and normalized throughput versus E_b/N_0 (dB) for R3P time and frequency correlated channels. Fully loaded system.



(a) BER versus E_b/N_0 (dB)



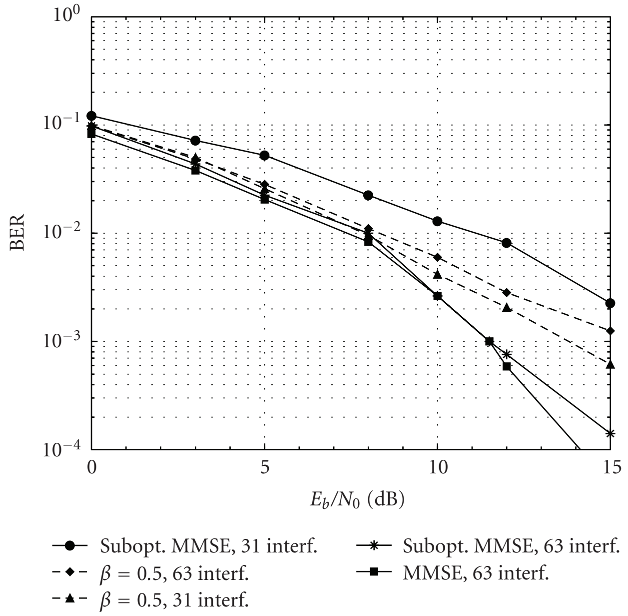
(b) Normalized throughput versus E_b/N_0 (dB)

FIGURE 6: BER and normalized throughput versus E_b/N_0 (dB) for $\beta = -1$ (MRC), $\beta = 0.5$, $\beta = 0$ (EGC) and $\beta = 1$ (ORC) when the system is fully loaded. Time and frequency correlated SUI-1 channel.

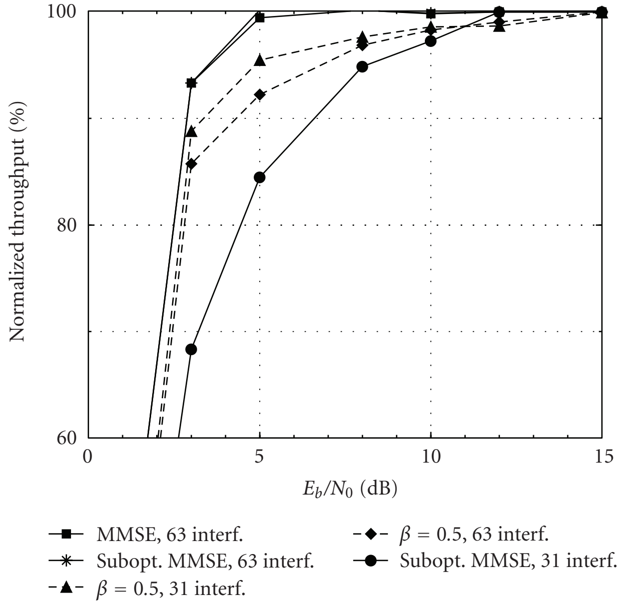
a value of $\beta = 0.5$ with respect to classical MRC can be observed both in terms of BER in Figure 5(a) and normalized throughput in Figure 5(b). These results enable a discussion on the impact of propagation channel on the performance at TCP level.

A comparison among PE with $\beta = 0.5$ and other linear combining techniques such as MRC, ORC, and EGC in SUI-1 channel model is presented in Figure 6 in fully loaded conditions. As can be observed, PE outperforms the other techniques both in terms of BER and normalized throughput. Note also that MRC and ORC techniques do not allow to achieve the maximum normalized throughput for SNRs of interest.

In Figure 7, a comparison among optimum MMSE, suboptimum MMSE, and PE with $\beta = 0.5$ is given in SUI-1 channel model. In particular, Figure 7(a) shows the BER versus E_b/N_0 (dB) for optimum MMSE in the fully loaded condition, suboptimums MMSE and PE with $\beta = 0.5$ for half and fully loaded system (note that suboptimums MMSE and PE have the same complexity). For the suboptimal MMSE solution we have assumed $\overline{\gamma}_{\max} = 11.5$ (dB) giving BER $= 10^{-3}$ in the case of optimal MMSE. As can be observed, MMSE gives the best performance as expected. For what concern suboptimal MMSE, its performance is similar to MMSE in fully loaded case, but it is outperformed by PE technique as soon as the number of interferers changes.

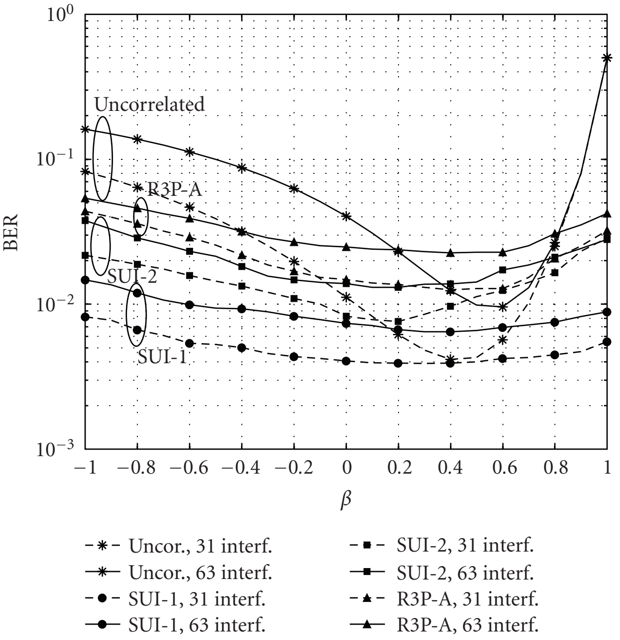


(a) BER versus E_b/N_0 (dB)

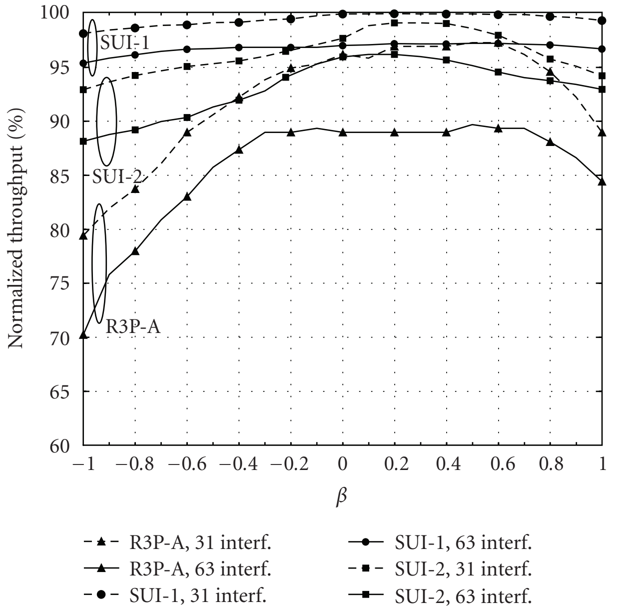


(b) Normalized throughput versus E_b/N_0 (dB)

FIGURE 7: BER and normalized throughput versus E_b/N_0 (dB) for time and frequency correlated SUI-1 channel. Comparison among MMSE, suboptimum MMSE and partial equalization with $\beta = 0.5$.



(a) BER versus β



(b) Normalized throughput versus β

FIGURE 8: BER and normalized throughput versus β varying the channel model and the numbers of interferers for $E_b/N_0 = 10$ dB.

Note that we are comparing parameterized combining techniques, such as suboptimums MMSE and PE with fixed value of the parameter. Since suboptimum MMSE is tuned for the fully loaded case, a reduction of the actual number of interferers implies an underestimate of the parameter $1/(N_u\overline{\gamma})$ in (12) towards the ORC scheme, thus emphasizing the effect of thermal noise with respect to the optimum choice of λ. Same considerations can be derived in terms of throughput by observing Figure 7(b).

By observing the performance in terms of throughput for the presented results, we can understand which SNRs are of interest to study the BER performance. In fact, it is rather common to find out in the literature asymptotical studies of the BER behavior (see, e.g., [22] and how to deal with with

SNRs of interest in [23]), but, as can be observed, the TCP throughput is affected by the adopted equalization technique for low SNRs and it is quite insensible to the physical level technique when the SNR increases.

Finally, in Figure 8 the impact of the PE parameter, β, on both the BER and the normalized throughput can be observed for a given SNR varying the channel models and the system load. In particular, in Figure 8(a) the BER at the decoder input is presented as a function of β for $E_b/N_0 = 10\,\text{dB}$ and for different system loads (half loaded and fully loaded system). A comparison among uncorrelated and correlated SUI-1, SUI-2, and R3P-A fading channels is also shown. As can be observed, the choice of β significatively affects the physical level performance when considering uncorrelated Rayleigh fading channels, while the BER behavior is more slightly affected by the values of β in correlated channels conditions. What is remarkable is that the optimum value of β (minimizing the BER) depends on many parameters: the channel model, the system loads, and the mean SNR. Note also the impact of an accurate choice of β on the performance in terms of throughput perceived by the user in Figure 8(b) in particular for SUI-2 and R3P-A channel models.

7. CONCLUSIONS

In this paper, we investigated the impact, at both physical and TCP levels, of different combining techniques for the downlink of MC-CDMA systems. By means of an integrated platform carefully taking into account all main aspects affecting the quality of service at the final user, the results in terms of bit-error rate at the decoder input and the TCP throughput for a huge file transfer in downlink have been derived. In our opinion, they enable relevant considerations on how equalization techniques that improve the performance at the physical level in the presence of interference, really affects the quality of service perceived by the final user. In particular, our numerical results show the impact of the different channel conditions (such as uncorrelated Rayleigh fading, time and frequency correlated Rayleigh fading, and SUI channels), system loads and combining techniques on the performance at physical and TCP level, allowing us to draw the following conclusions:

(i) the BER is more sensitive to the combining technique in uncorrelated channels than in time and frequency correlated channels;

(ii) the throughput is sensitive to the combining technique for low and moderate SNRs, while the impact of the combining technique is less evident when the SNR increases;

(iii) PE technique is less sensitive to the number of interferers rather than classical MRC or suboptimum MMSE, providing a good solution for MC-CDMA systems. This effect is still more evident in terms of throughput.

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