Clipping Noise Cancellation in Uplink MC-CDMA System Using Signal Reconstruction from Non-Uniform Samples

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***Abstract*— In this paper, an iterative signal reconstruction method is extended to cancel multi-user clipping noise in a uplink MC-CDMA systems. Clipping is the simplest method to overcome high peak-to-average power ratio of multi-carrier signals but it makes the multi-carrier signals distorted. Reconstruction methods use non-distorted samples to reconstruct distorted samples in the receiver but multi-user interference causes the methods do not work properly because all the received samples are distorted by clipping and interference and so there is no undistorted samples to be used in recovering clipped samples. On the other hand, multi-user interference cancellation methods do not work properly because clipping in the transmitter is a non-linear process and therefore this process increases the amount of multiple access interference (MAI). In this paper, we propose a joint MAI and clipping noise cancellation method. In the proposed method in each iteration a MC-CDMA detector is used for signal detection and then using non-uniform sampling (that forces known error positions due to clipping to be zero) and filtering process an error estimation is calculated and then canceled. Simulation results show that the proposed method improves the performance of clipped MC-CDMA systems in uplink.**

I. INTRODUCTION

Multi-Carrier Code Division Multiple Access (MC-CDMA) is an attractive multiple access scheme in wireless communications. MC-CDMA signals of different users are Orthogonal Frequency Domain Multiplexing (OFDM) signals that are spread in frequency domain [1]. OFDM has good advantages in multipath fading channels; this is because this system is able to convert a frequency selective channel to a set of flat fading sub-channels [2]. There are some other methods to join OFDM system with multiple access methods such as the methods described in [1]- [2]. According to the fact that MC-CDMA system is a combination of OFDM system with CDMA system, MC-CDMA has advantages and disadvantages of both systems.

Because of high peak-to-average power ratio (PAPR) of multi-carrier signals, multicarrier systems require expensive amplifiers with large dynamic ranges. The simplest method to mitigate high PAPR values is signal clipping and filtering before signal transmission. But, by clipping, signals suffer in-band distortion and out-of-band radiation [2],[3]. Furthermore, the digital-to-analog conversion of the clipped signals produces peak regrowth because of filtering at the output of D/A converters. It has been shown that by padding the original multi-carrier signal with zeros, clipping the over-sampled signal by properly chosen threshold values results in lower PAPR with negligible peak regrowth [4]. The effect of filtering on peak regrowth problem has been considered in [3].

In addition to clipping method, there are some other methods for PAPR reduction in MC-CDMA systems [5],[6] and [7]. Successive clipping and filtering, precoding methods, Partial Transmit Sequence (PTS) and Selective Mapping (SLM) are some of these methods [5]-[7]. In PTS method, parallel inputs to IFFT/FFT block are partitioned into smaller parts and multiplied by sequences which are selected to reduce PAPR; therefore after IFFT/FFT process, an multi-carrier signal with lower PAPR is produced and transmitted. In SLM method before IFFT/FFT, the symbols are multiplied by pseudo random sequences and then one of the sequences with the lowest PAPR value is chosen and transmitted. These two methods need side information in receiver to decode the received signal.

By considering that a MC-CDMA signal is an multi-carrier signal, it can be seen that over-sampling method can be applied to MC-CDMA systems to reduce effects of clipping and filtering. On the other hand, after padding the original signal with zeros in frequency domain, there are some redundancy in zero-padded signal that can be used for reconstruction of the original signal in receiver by signal reconstruction methods. But because of multi-user interference, the power of desired user's signal in uplink is very small in comparison with the power of the received signal, therefore the reconstruction methods can not work properly in such a noisy condition. In the other words, the reconstruction methods use undistorted

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samples to recover distorted samples but because of multi access interference (MAI) all of the samples are distorted.

To cancel MAI, there are some methods known as multi-user interference cancellation or multi-user detection methods [8]. But these methods can not work properly in the presence of clipping distortion in MC-CDMA systems. For example in case of using orthogonal spreading codes, clipping removes orthogonality among users and furthermore because of non-linear nature of clipping, this process can not be modeled as a linear process and so the performance of MAI cancellation methods severely degrades. These facts have motivated us to propose a method that jointly cancels MAI and clipping noise.

Our proposed iterative method in each iteration has a MAI cancellation procedure along with a clipping noise cancellation process. In fact, in the proposed iterative method in each step a detection method, which can be an interference cancellation technique is applied to received signal; then non-uniform sampling and filtering processes are applied to different users' signals reproduced after interference cancellation; and then an approximation of error due to clipping and residual interference is computed. By applying this approximation of error, the detection method performs better and it gives a better approximation of the signal in the next iteration. Our simulation results for Rician fading channels show that the proposed method improves the performance of oversampled MC-CDMA systems in BER (Bit Error Rate) performance without any extra bandwidth. This is because the extra bandwidth due to zero-padding is totally removed when the signal is filtered before transmission.

Following this introduction, the paper is organized as follows: the structure of MC-CDMA systems is briefly reviewed in section II. In section III, basis of the iterative method is described and based on it an iterative method for jointly clipping noise and MAI cancellation is proposed. Section IV presents the simulation results and the conclusion is presented in section V.

II. System Description

A complex base-band MC-CDMA signal for l^{th} user can be expressed as follows:

$$s_l(t) = \sum_{i=-\infty}^{+\infty} \sum_{n=0}^{N-1} \gamma_l(i) b_l(i) c_l(n) e^{j2\pi n f_0 t}, \quad (1)$$

where f_0 denotes the sub-channels spacing and it is set to $f_0 = \frac{1}{T}$ to produce orthogonal sub-carriers, where T is time duration of each input symbol(symbol time). N is the number of sub-carriers that is processing gain of MC-CDMA system. In (1), $\gamma_l(i)$ is the power control coefficient for l^{th} user in i^{th} transmission. If there is no power control in cellular system, all the power control coefficients are set to 1 [1]. $b_l(i)$, and $c_l(n)$ denote i^{th} binary data of l^{th} user and spreading code of l^{th} user assigned to n^{th} subcarrier, respectively. After base-band modulation, the signal is modulated with carrier frequency f_c, and then we have following real signal in the transmitter:

$$x_l(t) = Re\{\sum_{i=-\infty}^{+\infty} \sum_{n=0}^{N-1} \gamma_l(i) b_l(i) c_l(n) e^{j2\pi(nf_0+f_c)t}\}. \quad (2)$$

For measuring amplitude fluctuations of multicarrier signals, the value of PAPR is a good criterion. In uplink, signal of each user is clipped and filtered separately and signals of all users are added in the base-station receiver with different delays. PAPR value of each user signal is defined as follows [2]:

$$PAPR = \max \frac{|s_l(t)|^2}{P_{ave}^{(l)}} : for\ l^{th} user, \quad (3)$$

where $P_{ave}^{(l)}$ is the average power of the multi-carrier signal of l^{th} user:

$$P_{ave}^{(l)} = E\{|s_l(t)|^2\}, \quad (4)$$

where $E\{.\}$ is expectation operator. From (1) and (3), it can be seen that if the components of the summation are in the same phase, the amplitude of the multi-carrier signal will be very much larger than its mean value and therefore PAPR of the multi-carrier signal will be large. Fig.1 shows the block diagram of uplink MC-CDMA system which is used in the analysis of this paper. Bold symbols represent vector quantities. As it can be seen in Fig.1, information symbols of each user are spread by the spreading sequence of that user in the way that the data are copied with rate N, which is the number of sub-carriers, and multiplied by the signature sequence of that user. Then the spread data of each user are zero padded. After that the MC-CDMA signal is produced by an IFFT operation. Padding zeros reduces the PAPR of the signal and acts as an over-sampling method that helps the reconstruction process of distorted samples at the receiver. The MC-CDMA signal before transmission is clipped and filtered. The resulted signal is transmitted through a communication channel modeled in this paper as a multi-path Rician fading channel which is specific for each user. Sum of these signals produces input signal of base-station receiver. By assuming a multi-path fading

[1]In uplink, power control coefficients are chosen so that power of all users' signals in the receiver be the same but in downlink a closed looped power control is applied to ensure that all users have desirable bit error rate and therefore, power control coefficients are determined by this control loop.

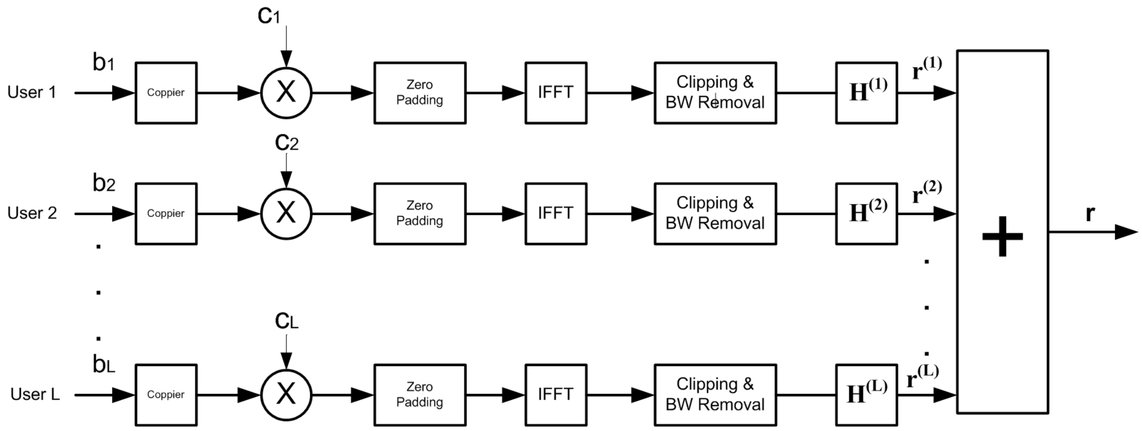

Fig. 1. The Block Diagram of an uplink MC-CDMA system, **r** is received signal in base-station.

channel, the base-band received signal at the input of the receiver is as follows:

$$r(t) = \sum_{l=1}^{L} r_l(t), \quad 0 \leq t \leq T \tag{5}$$

where

$$r_l(t) = h^{(l)}(t) * s_l(t) + \xi_l(t), \quad 0 \leq t \leq T \tag{6}$$

in which $s_l(t)$, and $\xi_l(t)$ are the base-band transmitted signal, and a base-band zero mean Gaussian random noise related to user l, respectively. $*$ denotes the convolution operator and $h_l(t)$ is multi-path fading channel impulse response related to user l that can be modeled in discrete domain as an FIR filter with Rician distributed weights. By using cyclic prefix(CP), we have circular convolution in discrete domain that makes possible to use low complexity single tap frequency domain equalizers in multi-carrier receivers [9]. In discrete domain, by using CP, (6) can be written as follows:

$$r_l[n] = h^{(l)}[n] \otimes s_l[n] + \xi_l[n], \quad 0 \leq n < N \tag{7}$$

where $\otimes$ denotes the circular convolution operator. In Fig. 1, we have:

$$\mathbf{H}^{(l)} = diag(FFT\{h^{(l)}[0], h^{(l)}[1], ..., h^{(l)}[L'], 0, ..., 0\}), \tag{8}$$

where $\mathbf{H}^{(l)}$ denotes channel coefficients in frequency domain for l^{th} user in matrix form ($N \times N$ matrix) and therefore the number of zeros in the above equation is $N - (L' + 1)$ where $L' + 1$ is the length of the FIR filter denoting the channel length, i.e., the number of resolvable paths. These coefficients are random variables with Rician or Rayleigh distribution and may vary with time in each multi-carrier block over fast fading channel.

III. The iterative Method

In this section, after reviewing the iterative method, we will propose an extension of the method that is a technique to jointly cancel clipping distortion and MAI in uplink MC-CDMA system. The iterative technique has been first proposed in [10] for interpolation noise cancellation and it has been shown that this method can be used for suppression of distortion noise caused by any linear or nonlinear distortion source under some convergence conditions. In fact, without explicitly knowing the transform function of the distortion source, the iterative method gives an inverse of the distortion function by placing it in iterations [11]. In [4] the authors have used the iterative method for clipping noise cancellation in OFDM systems. In this paper we extent the method to jointly cancel MAI and clipping noise. The iterative method is expressed as follows:

$$x_n(t) = \lambda PSx(t) + (I - \lambda PS)x_{n-1}(t) \tag{9}$$

where S and P are sampling operator and low-pass filtering, λ is a relaxation factor and $x_n(t)$ is the output of n^{th} iteration and an proper initial condition is $x_0(t) = PSx(t)$. Fig.2 shows schematics of the iterative method. By denoting the error operator as $E = I - PS$ and by replacing it in the block diagram of Fig.2, we have another equivalent block diagram that can be seen in Fig.3. In Fig.3, F_n is the system function of the iterative method with n iterations. Then, by choosing $\lambda = 1$, we have(see Fig.3):

$$F_n = [(E + I)E + I...]E + I = I + E + ... + E^n \tag{10}$$

where I is the identity operator. Whenever $n \longrightarrow \infty$, then we have $F_n \longrightarrow F = \frac{I}{I-E} = (PS)^{-1}$, if only if $\|E\| < 1$. In other words, if and only if the power of error due to nonuniform sampling and filtering be less than the power of input signal, the distortion caused by the nonuniform sampling converges to zero.

Now we try to use the iterative method to reconstruct clipped multi-carrier signals in the receiver. In our previous paper, we have shown that this idea works for clipping noise cancellation purposes in OFDM system; in fact we have shown that for OFDM signals, non-uniform sampling & filtering have nearly similar results with clipping & filtering. Furthermore, the method of [4] can be straight forwardly be applied in downlink MC-CDMA systems. In downlink MC-CDMA system, multi-carrier signals of different users in base-station are added in the synchronous manner and the resultant signal, which may have large PAPR values, is clipped and filtered to mitigate high peak values. Therefore in the receiver of downlink MC-CDMA system, the received clipped signal can be reconstructed using the iterative method; then data of different users can be extracted using their own spreading codes. Simulation results show the convergence of the iterative method for such systems. In uplink MC-CDMA system each user produces its multi-carrier signal that may have large peak values. In the transmitter, the signal is clipped and the resulted signal is transmitted; therefore in the base-station receiver, there is a sum of some clipped signals. For signal reconstruction, because of clipping, we must resolve our desired signal among other users' interfering signals. But for resolving our desired signal, we must use one of different single-user or multi-user detection (or interference cancellation) methods. Performance of detection methods are degraded due to clipping because in an MC-CDMA system using orthogonal codes, after clipping, signals of different users will not be orthogonal. Above argument shows that a joint method for signal reconstruction and multi/single user detection will gain us a good performance for uplink MC-CDMA systems. Above facts encourages us to propose an uplink MC-CDMA system with the iterative method but the block PS is changed to more complex block that is containing multi-user detection / interference cancellation in each iteration. This block is shown in Fig. 3.

In the proposed iterative method, each iteration is consisted of a type of MC-CDMA detector such as single-user detector or multi-user detector that can be seen as a method doing signal mapping to original data constellation (binary) followed by processes of zero-padding, FFT and non-uniform sampling with filtering. It must be noted that in binary MC-CDMA system, the input bit only changes the polarity of transmitted signal for each user then because of knowing all the signature sequences in the BTS, the receiver of uplink MC-CDMA knows the locations of clipping errors for each user so non-uniform sampling only forces known error locations to zero. The resultant signal is filtered and the signals of different users are added. After that, by using the received signal that is chosen as reference signal and output of previous iteration, the error signal is estimated. It must be notified that the estimated error signal consists of error due to clipping and error due to MAI. All theses processes are repeated to provide us better estimations of clipping noise. Moreover by reconstructing the clipped signals, the MC-CDMA detection method gains better performance.
Our simulation results presented in the next section show that for Rician fading channels with Additive White Gaussian Noise, i.e. AWGN, the iterative method can efficiently mitigate clipping distortion for uplink MC-CDMA system without using any side information such as those of PTS and SLM techniques [5]-[7].

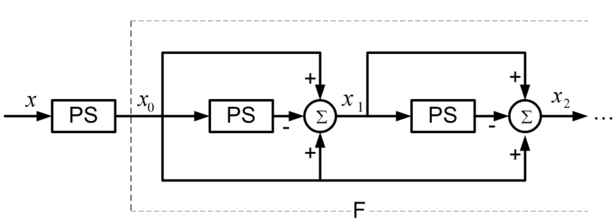

Fig. 2. The Block Diagram of the Iterative Method.

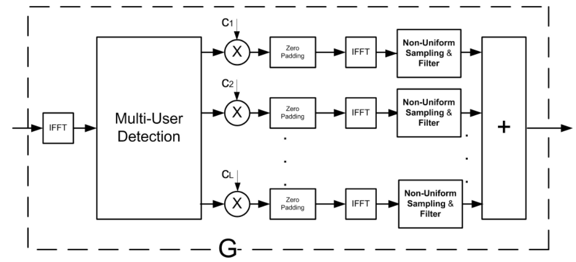

Fig. 3. The function replaced the process PS in the proposed method

IV. Simulation Results

In order to evaluate the performance of the proposed method over statistically independent Rician flat fading sub-channels, we consider a typical binary MC-CDMA uplink system with spreading gain of $N = 32$ where N is also number of sub-carriers for multi-carrier system and Hadamard-Walsh codes are used for spreading. In this system, we oversample the symbol sequence by rate of 4. The rate of 4 is chosen because in [3], it has been shown that for OFDM signals it is a near optimum point to reduce probability of clipping with a moderate complexity. It means that the oversampled signal is produced by inserting $3 \times 32 = 96$ zeros at the end of the sequence and therefore, the size of IFFT/FFT module becomes $4 \times 32 = 128$.

The amount of MAI can be calculated using Signal-to-Interference Ratio (SIR) that is defined as:

$$SIR = \frac{\textit{average power of desired user}}{\textit{average total power of interfering users}} = \frac{P}{(L-1)P} = \frac{1}{(L-1)} \quad (11)$$

Equation (11) is obtained by assuming that there is power control in uplink and then all users have the same power in the base-station receiver.

Fig. 4 shows the BER performance versus $\frac{E_b}{N_0}$ for a 23-user uplink MC-CDMA system using the proposed joint multi-user interference and clipping noise cancellation method. The proposed iterative method uses the decorrelator multiuser detection method with clipping ratio of $\sqrt{3}$ and with the optimized relaxation factor of λ=0.3, 0.2, and 0.1 for the first, second and third iterations, respectively. It can be seen that for BER of 5×10^{-4} we see approximately 3 dB improvement in $\frac{E_b}{N_0}$ performance for only one iteration. Fig. 5 shows the BER performance versus $\frac{E_b}{N_0}$ for a synchronous 20-user uplink MC-CDMA system with decorrelator multiuser detection method with clipping ratio of $\sqrt{2}$ and with optimized relaxation factor of λ=0.3, 0.2 and 0.1 for the first, second and third iterations, respectively. As it is seen from Fig. 5 for BER of 5×10^{-4} there is at least 2 dB improvement in $\frac{E_b}{N_0}$ performance by using only one iteration. Fig. 6 shows same simulation condition with fig. 5 but with less users L=17. It can be seen that by decreasing number of users, BER values improve.

It can be seen from figs. 4 to 6 that the proposed method considerably improves the BER performance of the clipped MC-CDMA system for different values of clipping threshold. Furthermore, by increasing the number of iterations, the BER performance improves for $\frac{E_b}{N_0}$ values more than 10 dB in conditions of figs. 4 to 6. This fact shows that, for sufficiently high values of $\frac{E_b}{N_0}$, the joint method reconstruct the original signal for commonly used threshold values of clipping.

V. Conclusion

In this paper, an iterative method for joint clipping noise and interference cancellation in uplink MC-CDMA system has been proposed. The proposed method, in each iteration, uses a single-user or multi-user detection method accompany with non-uniform sampling & filtering process which are applied to different users' signals; then using the received signal as reference signal, an approximation of error due to clipping and residual interference is computed and removed from the received signal. Computer simulations show that this method improves the performance of the clipped MC-CDMA system considerably in uplink for practical values of clipping threshold without using any extra bandwidth.

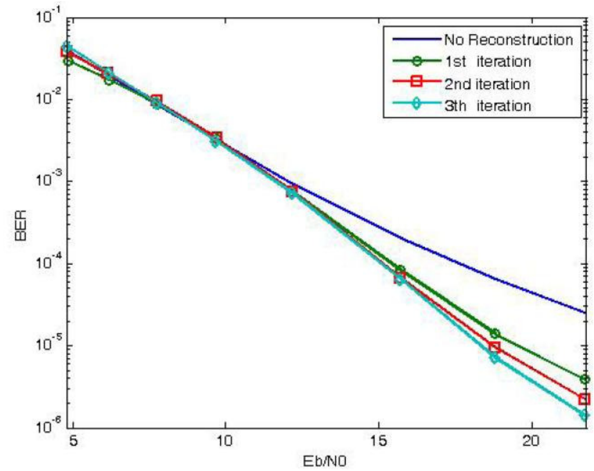

Fig. 4. BER versus $\frac{E_b}{N_0}$ with decorrelator, clipping ratio of $\gamma = \sqrt{3}$, Number of users L=23, SIR=-13.4 dB.

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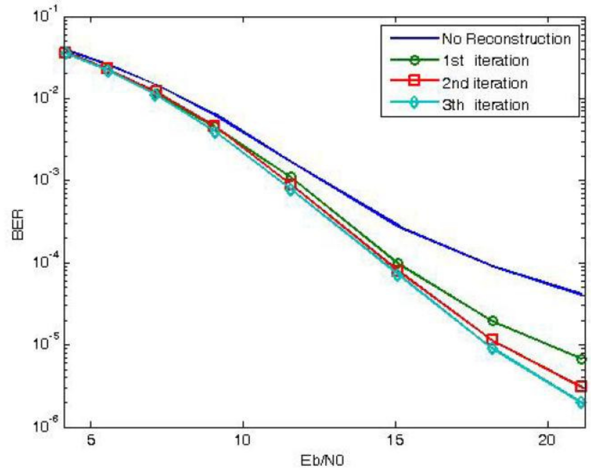

Fig. 5. BER versus $\frac{E_b}{N_0}$ with decorrelator, clipping ratio of $\gamma = \sqrt{2}$, Number of users L=20, SIR=-12.79 dB.

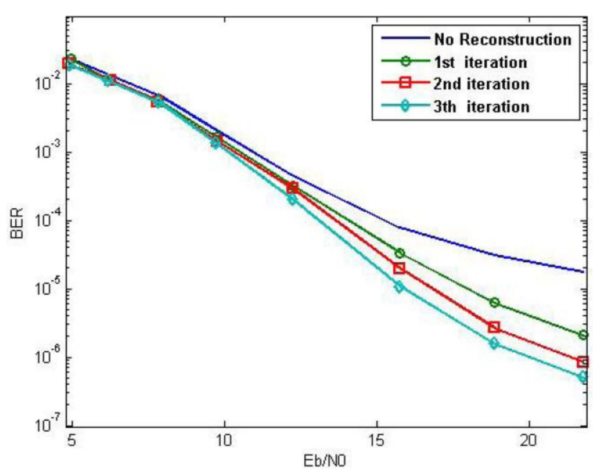

Fig. 6. BER versus $\frac{E_b}{N_0}$ with decorrelator, clipping ratio of $\gamma = \sqrt{2}$, Number of users L=17, SIR=-12.04 dB.