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DETECTION SCHEMES FOR MC-CDMA (4G) MOBILE SYSTEM: A REVIEW

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Abstract: *In present mobile communication scenario where users demand is more for high speed data rather than voice we need more bandwidth to accommodate data as well as voice. 4G standards are being rolled out in different parts of world which are said to give data rate up to 20 Mbps. Various voice and multimedia applications are possible only with this kind of data speed. Even though orthogonal frequency division multiplexing-long term evolution (OFDM-LTE) is the basic radio technology being used to provide 4G implementation but peak-to-average-power ratio (PAPR) and multipath fading are some problems with OFDM-LTE, which encourage the employment of multicarrier code division multiple access (MC-CDMA) as an alternate technology for 4G systems. Moreover MC-CDMA is also being discussed as basic technology for fifth generation mobile systems (5G). MC-CDMA is basically a combination of CDMA and OFDM. It provides frequency diversity to the transmitted data due to which problems like PAPR and multipath fading are mitigated. In this paper various detection schemes for MC-CDMA systems have been reviewed under different parameters.*

Key Words: *Multi-carrier code division multiple access (MC-CDMA), multiple access interference (MAI), Multiuser Detection (MUD).*

1. Introduction: MC-CDMA

Code Division multiple access (CDMA)[1] has been successfully implemented across the globe to deliver wireless mobile services but in present scenario where more thrust is for data rather than voice, CDMA cannot be relied upon, since it is a single carrier system hence cannot deliver high data rates. Apart from this inter symbol interference (ISI) and multipath fading are some other impediments in the way of CDMA to deliver high data rates [2]. So when moving into fourth generation of wireless communication systems (4G) in which data is transmitted at a rate as high as 1 Giga bits-per-second (bps), single carrier systems are not suitable, because Inter symbol interference (ISI) and multipath propagation are major impediments.

In OFDM [3, 4] channel bandwidth is divided into a number of sub channels, with each of equal bandwidth utilizing a subcarrier to transmit a data symbol. Since all the subcarriers are orthogonal to one another over one symbol period hence OFDM technique can transmit a large number of different data symbols simultaneously, enabling this technology to support high data rate transmission. Despite all these advantages, the conventional OFDM systems can support only a single user raising the need for a multicarrier multiple access systems.

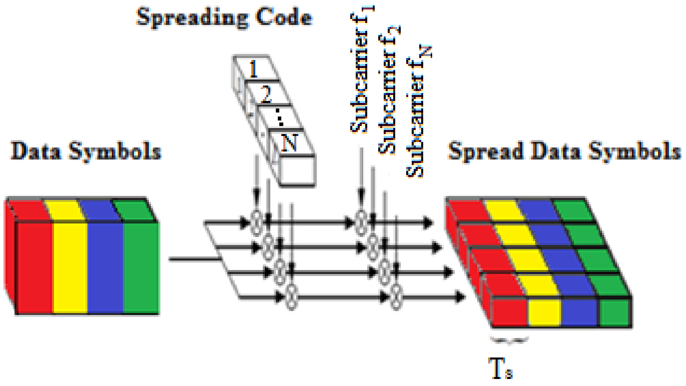

Fig. 1 MC-CDMA Transmitter model

MC-CDMA [5, 6, 7] is termed as a combined technique of OFDM and CDMA. MC-CDMA converts original data stream into frequency domain with the help of different subcarriers using a given spreading code as shown in Fig.1. So in this way different parts of a data symbol are sent on different subcarriers thereby achieving frequency diversity as shown in Fig. 2.

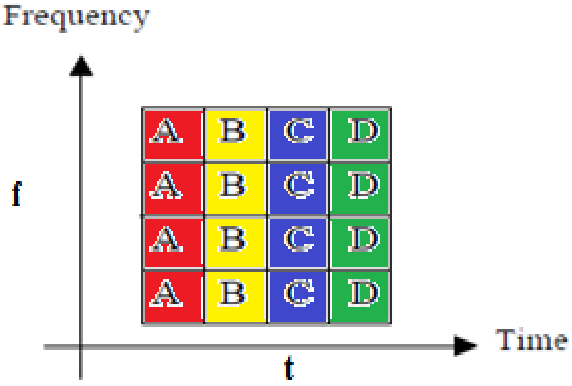

Fig. 2 Frequency Diversity of symbols

This is the main advantage of the MC-CDMA scheme [8, 9]. This is the reason why MC-CDMA systems are immune to fading because all the subcarriers cannot go into deep fade simultaneously. In MC-CDMA systems, different users share the same frequency band and same user is divided among different frequency band which explain the concept i.e. why MC-CDMA systems are immune to multipath fading because there is very less chance that all the subcarriers of a particular user will go into deep fade at the same time [10,11].

As explained earlier, in MC-CDMA by selecting mutually orthogonal subcarriers interference free multicarrier signal transmission is possible, but we know that in a wireless environment orthogonality of subcarriers cannot be maintained. So at the receiver end interference occurs which is called as multiple access interference (MAI) and in case of asynchronous transmission (uplink) MAI is inherent because of different timing of different users. Frequency selective fading, non-linear power amplification and near-far are some other factors which contribute towards non-orthogonality of subcarriers. In this paper various detection techniques for MC-CDMA mobile systems are discussed and their performances are evaluated in the context of MAI and near-far effect.

The paper is divided into 9 sections. In section 2 Single user detection has been explained. Section 3 explains Multiuser detection. In Section 4 optimum multiuser detector has been discussed. Section 5 covers linear detector. Section 6 describes a non linear detector. Section 7 is for simulation & discussion. Section 8 concludes the paper.

2. Single-User Detection (Matched filter detection)

The single user detectors [12] to detect MC-CDMA signals are very easy to implement. All we have to do for this purpose is to use one matched filter to detect one signal and a decision threshold device to give a correct decision about the bit received. Suppose if there are K numbers of users we need K number of matched filters and equal number of decision devices because single user detectors demodulate all the signals independently.

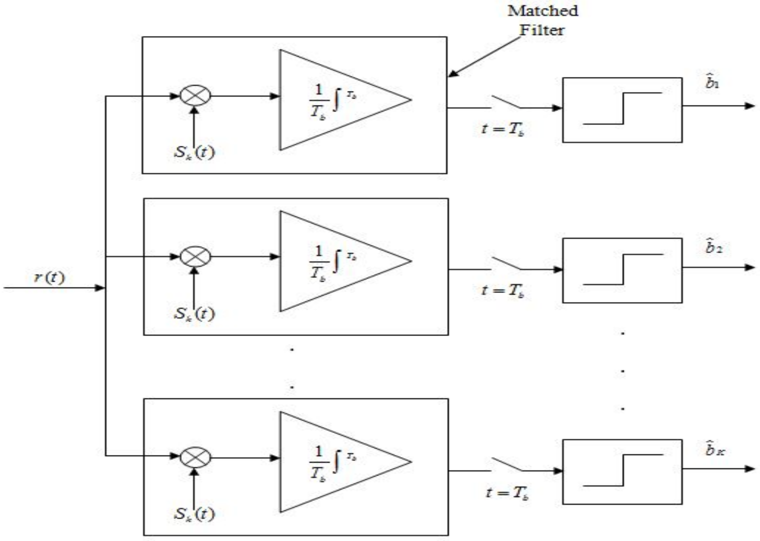

Fig. 3 Single user (matched filter) detector

Received signal r (t) is given as

$$r(t) = \sum_{k=1}^{K} b_k A_k S_k(t) + n(t), t \in [0, T] \tag{1}$$

where $b_k \in [-1, +1]$, is the kth users transmitted bit

A_k is the kth user's amplitude ,

S_k is the kth user's waveform (code e.g. PN sequence) ,

n(t) is additive white Gaussian noise (AWGN).

As shown in Fig. 3 received signal r(t) is multiplied by each different kth waveform (spreading orthogonal code).So autocorrelation with the same waveform in composite signal r(t) selects the desired signal at the output of each matched filter(correlator circuit). Single user detectors are simple to implement and moreover they do not require knowledge about channel or users amplitudes, but at the same time single user detectors cannot eliminate MAI effectively and also they are not near-far resistant and hence need a proper power control. Matched filters are optimum for white Gaussian noise but not for MAI, So single user detector cannot give optimum detection.

3. Multiuser Detection

Since single user detectors are not optimum and cannot effectively eliminate MAI. In early 1980 Sergio Verdu in [13,14] proposed the first optimal multiuser detector, which is also termed as Maximum-Likelihood(M-L) detector. The basic idea behind multiuser detection was to take into account all the information of all the users simultaneously and give the decision according to maximum likelihood criterion over one bit period. In this scheme bits with the highest probability of occurrence are detected. This concept is similar to diversity concept in communication where multipath signals are exploited to achieve diversity. The very purpose of multiuser detection is to find out different ways to process outputs of matched filters so that the transmitted bit can be detected accurately. The basic difference between single user detectors and multiuser detectors is that in single user detectors, interference term (MAI) is taken as noise term whereas in multiuser detection MAI term is used as a useful information to detect the received bits correctly. The basic operation of multiuser detection algorithm is to cancel out effect of MAI on each user data bit and jointly detect the data bits. The MUD concept has been shown in Fig. 4, where outputs of matched filters are processed according to MUD algorithm and bits are detected accordingly.

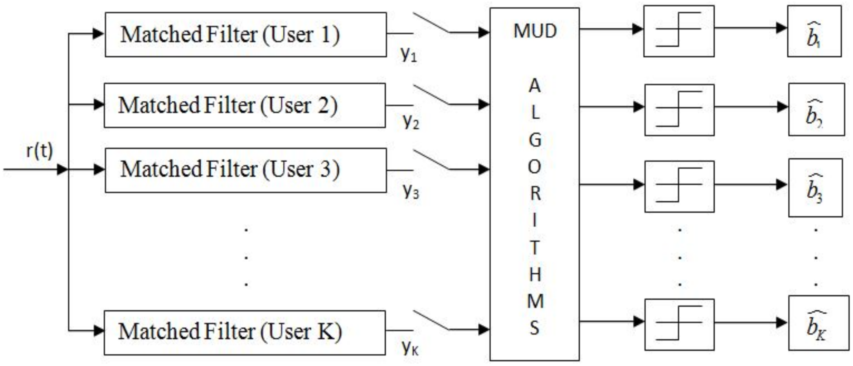

Fig. 4 Multiuser Detection

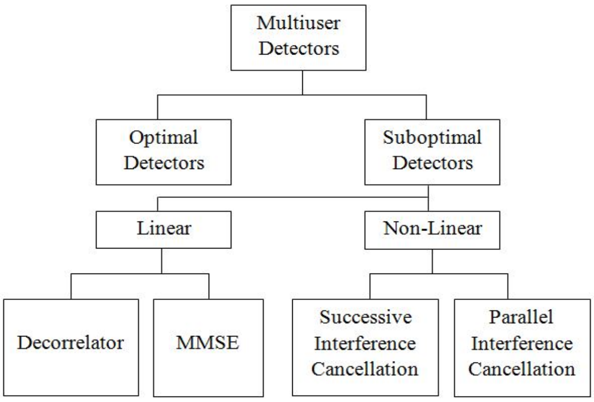

Fig. 5 Classification of Multiuser Detectors

MUD algorithms are broadly classified as optimal and suboptimal. Optimal detector perform an exhaustive search to detect correct data bits and for this it has to perform 2^k number of calculations, which is a complex and time consuming task. Various Suboptimal detectors [15] have been proposed which perform the detection with much lesser number of calculations as compared to optimum detector but with slight degradation in bit error rate (BER) performance. In Fig. 5 classification of various multiuser detectors is shown. Suboptimal detectors are further classified as linear detectors and non-linear detectors.

4. Optimum Multiuser Detector

The optimum decoding in the presence of AWGN is to compare all the received sequences with all the possible code sequences. So this method can achieve a maximum likelihood (M-L) performance but complexity of the system goes on increasing with the increase of number of users [16]. For a K number of users it has to do 2^K number of calculations, which is the main drawback of M-L detector. It means system will become more complex with the increase in number of users. So they are not suitable for a system with large number of users. For this very reason suboptimum detectors have been developed.

The optimum multiuser detector detects by jointly maximizing the likelihood functions for K users by choosing bit combination $\{b_1, b_2, \ldots, b_K\}$ that minimize the mean square error (MSE) between the estimated signal and the actual composite received signal. The received signal r(t) is the sum of received signals for all K users, plus noise. For K number of users in a synchronous MC-CDMA system, the outputs of matched filters as shown in Fig. 4, can be given as $y = [y_1, y_2, \ldots, y_K]$. In the matrix form

$$y = RAb + n \ , \tag{2}$$

where b is a vector of K user's symbols i.e. $b = [b_1, b_2, ..., b_K]^T$.

A is a diagonal K×K matrix of user's amplitudes,

R is a K×K cross correlation matrix of the user's spreading sequences,

n is additive white gaussian noise (AWGN), it can be given as $n = [n_1, n_2, \ldots\ldots, n_K]^T$.

Now the optimum(maximum likelihood) detector of data vector b is given as

$$\hat{b} = \arg \min_{b} |y - ARb|^2 \ , \tag{3}$$

where the notation arg $\min_b$ refers to the value of b that minimizes the quantity within braces. This method searches all possible b vectors to determine the one that minimizes the square error between matched filters outputs y and the predicted value . So we have to choose ƃ such that estimated signal is closest to the received signal . The optimum estimate of ƃ will minimize the probability of error. The equation above can be further written as:

$$\hat{b} = \arg_{b\in\{-1,1\}} \max\left(2b^T y - b^T ARAb\right) . \tag{4}$$

So bit combination which maximize above expression will be selected by optimum detector.

5. Linear Detectors

5.1 Decorrelating Detector

We know that for a synchronous K user MC-CDMA system, outputs of matched filters as shown in Fig. 6 can be given in matrix form as:

$$y = RAb + n \ .$$

Now if we multiply both sides by R^{-1} (inverse of R)

$$R^{-1}y = R^{-1}RAb + R^{-1}n \ .$$

Since $R^{-1}R = I$ where I is the identity matrix and IAb≡Ab

So,

$$R^{-1}y = Ab + R^{-1}n \ . \tag{5}$$

From the above equation (5) it is clear that decorrelator linearly transforms the outputs from conventional detector. It has been demonstrated that a decorrelator detector [17, 18] completely eliminates the MAI and is near-far resistant but it generally increases the level of background noise. The biggest advantage of decorrelator is its low complexity which varies linearly with K. As shown in Fig. 6, for a K number of users output of matched filters gets multiplied by inverse of R.

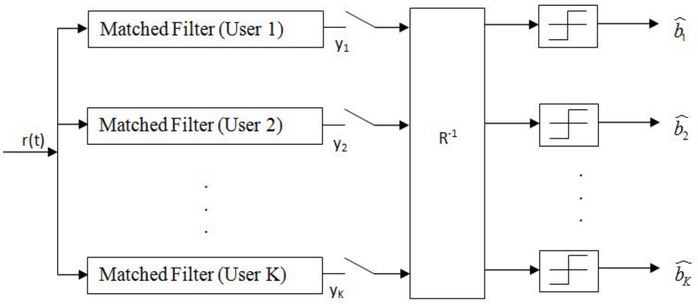

Fig. 6 Decorrelator multiuser detector

5.2 MMSE Detector

MMSE is another linear detector which calculates the mean square error between estimated bit and received bit. In MMSE detection received signal y is multiplied by factor $(R + \sigma^2 A^{-2})^{-1}$ as in Fig. 7, where σ is the variance of noise and it is clear that if noise variance (σ) approaches to zero then performance of MMSE detector [19, 20, 21, 22] is the same as that of decorrelator detector but if noise variance (σ) increases then performance of MMSE detector degrades and approaches towards matched filter detector. MMSE detector has been found to be better than decorrelator because it eliminates MAI as well as noise and unlike decorrelator detector, it does not enhance background noise but complexity of MMSE is a problem because it involves the inversion of a large size of matrix leading to more computational complexity.

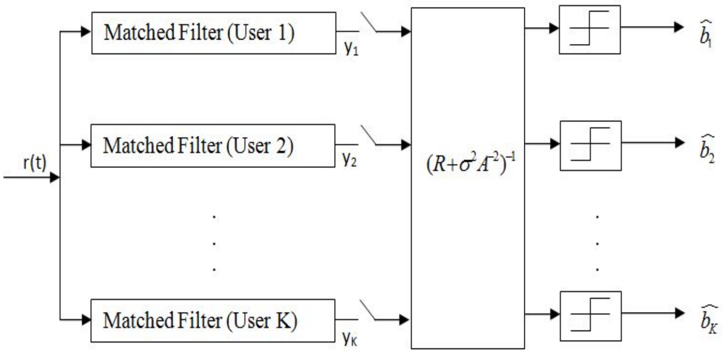

Fig. 7 MMSE multiuser detector

6. Non Linear Detectors

6.1 Successive Interference Cancellation (SIC)

Successive interference cancellation [23, 24, 25,26] is a non-linear type of multiuser detector. The basic principle behind this detector is that it works in multistage where it serially cancels the interference from the outputs of the matched filters. SIC is based on decision feedback algorithm. In SIC different users signal are actually arranged in ascending order with the strongest user in first place. First of all contribution of strongest signal is cancelled and then it is the turn of second strongest signal and this process is repeated until contribution of all users is cancelled out from the received signal.

In equation (6) below, MAI due to strongest users has been subtracted from the received matched filter output y_j of the j^{th} user to detect bit b_j.

$$\hat{b}_j = sign\left(y_j - \sum_{k=j+1}^{K} A_k \rho_{kj} \hat{b}_k \right) \tag{6}$$

A_k is amplitude of k^th^ bit, ρ_{kj} is cross-correlation of kth and jth bit and $\hat{b}_k$ is estimated bit of kth user. As shown in Fig. 8, in this detector subtraction is done serially and after each stage of subtraction MAI is cancelled out.

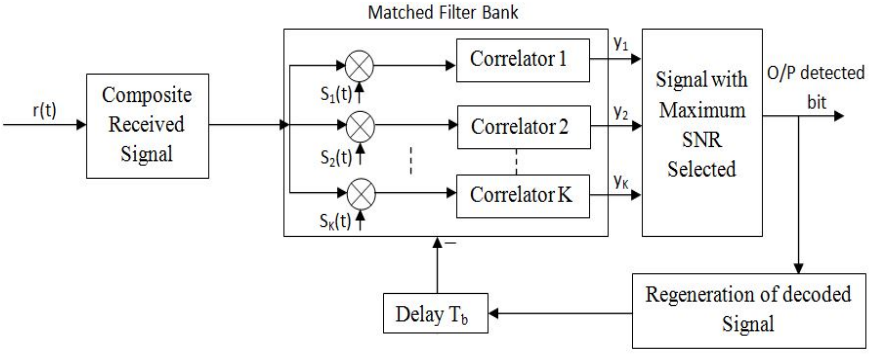

Fig. 8 SIC multiuser detector

Advantage of SIC is that a near complete elimination of MAI is possible if large numbers of stages are introduced and on the other hand there are also some drawbacks associated with this method. One of the major drawbacks is the delay or latency problem which increases with the increase of number of stages. Another drawback of SIC detector is that in a perfect power control scenario in uplink, sorting of users signal with high or low power becomes difficult so it may happen that signal which is detected first would be presented as most interferer and signal detected last as least interferer even though all signals are at same power level. So this may degrade overall performance of the system.

6.2 Parallel Interference Cancellation

Unlike SIC, Parallel interference cancellation (PIC) [27, 28] subtracts all estimated signals of users from the composite received signal. Similar to SIC, PIC also works in multiple stages. In each stage, residual error is left which is subtracted in next stage and this process is stopped when there is no error left as depicted in Fig. 9. In this way a complete MAI estimation is achieved. So, a PIC detector simultaneously removes interference from each user's signal. In comparison with SIC, performance of PIC is better if perfect power control is imlemented because like SIC it does not have to sort out user's signal with different power levels and also delay or latency is same for any number of users because it performs in parallel.

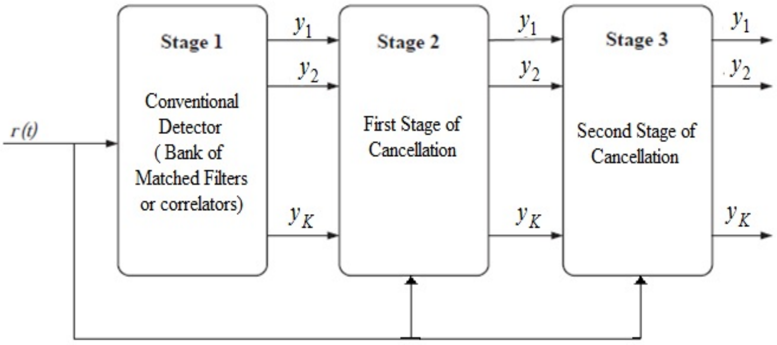

Fig. 9 PIC multiuser detector

Unlike SIC where only MAI of strongest user is subtracted from the second strongest user's signal, in PIC MAI of all the users are subtracted in a parallel manner from the desired user's signal whose bit has to be detected. As shown in equation 7, MAI of all the users is subtracted from matched filter output y_j to detect the bit b_j.

$$\hat{b}_j = sign\left(y_j - \sum_{k \neq j}^{K} A_k \rho_{kj} \hat{b}_k \right) \tag{7}$$

PIC is faster in comparison with SIC, but it needs perfect initial amplitude estimation. PIC gives better BER performance than SIC under equal power control scenario.

7. Complexity & Latency of MUD detectors

Complexity of a multiuser detector can be defined as the number of iterations needed to detect the bits of different users for one bit period whereas latency is basically the time taken by a multiuser detector in detecting bits of different users. Table 1, gives an idea about the complexity of different detectors and their respective latency (delay) [13]. It can be analyzed that SIC detector looks better as far as complexity is concerned since it takes only K number of iterations which is lowest among all the detectors. However in case of latency (delay) both SIC and PIC performs poorly because detection is performed in a number of receiver stages. In case of SIC and PIC latency is one bit per receiver stage. Latency of optimum (M-L), MMSE and decorrelator detectors is minimum (equal to 1) among all the detectors as there is only one receiver stage. Complexity of optimum detector is highest which is equal to 2^K number of iterations. So an optimum detector is not preferred for practical implementation.

Table 1: Complexity and latency of different detectors

MUD	Complexity Order	Latency
Optimum/Max Likelihood (M-L)	2^K	1
Decorrelator	K^2	1
MMSE	K^2	1
SIC	K	K
PIC	PK	P
Matched filter(single user detector)	K	1

* K is no of users, and P is receiver stages.

8. Simulation & Discussion of Results

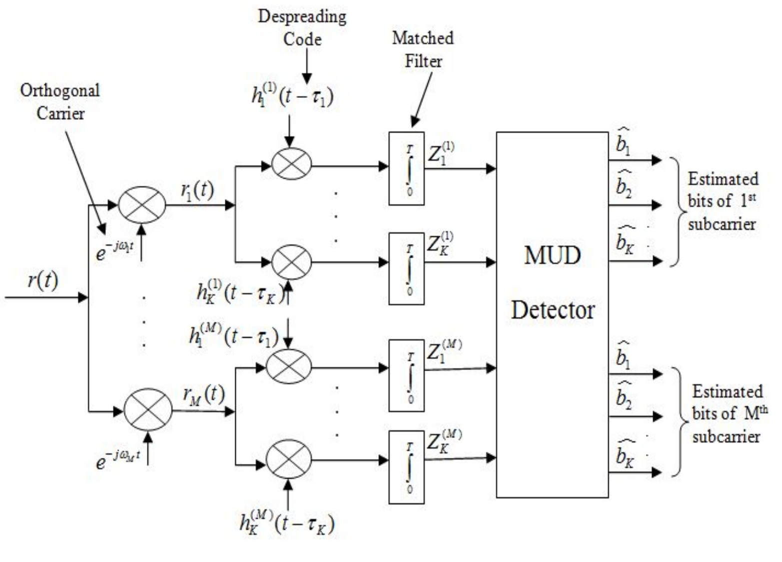

Fig. 10 Multiuser MC-CDMA detector

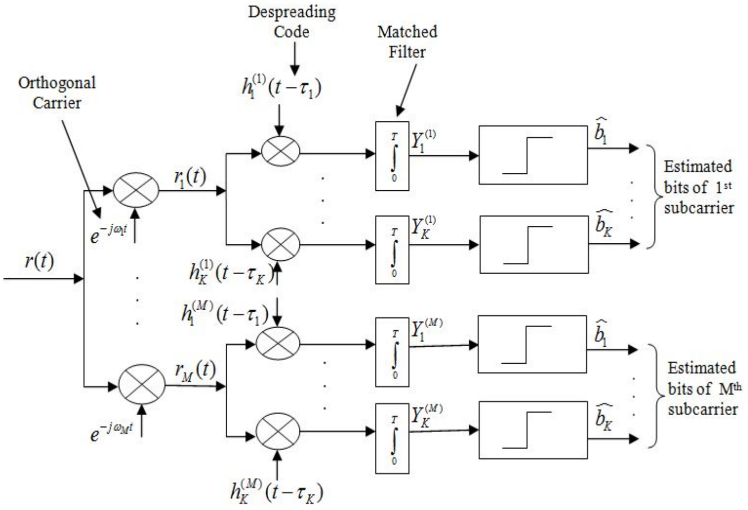

Fig. 11 Single user (matched filter) MC-CDMA detector

In this section, single (matched filter) detector and multiuser detectors have been compared based on different parameters. Fig. 10 shows a multiuser detector and Fig. 11 is for single user (matched filter) detector. Composite signal r(t) is received at the receiver where orthogonal subcarriers are recovered by FFT(fast fourier transform) and after this step different user bits are recovered by multiplying with spreading codes.

In the Fig. 10 and Fig. 11 above, composite signal r(t) received has been divided among M number of subcarriers. Subcarrier f_1 carries a small part of data of all the users and this data is spread by spreading code h_1 i.e. 1^{st} chip. So in this way entire signal (from subcarrier f_1 to f_M) is coded by different spread sequences from S_1 to S_K and received signal on m^{th} subcarrier can be given as:

$$r_m(t) = \sum_{k=1}^{K} \left[A_k S_{k,m}(t).b_k(t) \right] + n(t)$$

Where,

A_k is the amplitude of k^{th} user ($k = 1, \ldots, K$)

M is the total number of sub-carriers,

$b_k(t)$: k^{th} user's transmitted bit

$S_{k,m}(t)$: k^{th} user's spreading sequence for the m^{th} sub-carrier,

$S_k(t) = \{S_{k,0}(t), S_{k,1}(t), \ldots, S_{k,M}(t)\}$: k^{th} user's spreading code over all sub-carriers, $\omega_m = 2\pi f_m$, where f_m (m=1, …, M) are the subcarrier frequencies.

For the simulation purpose, a total of 16 numbers of users are taken. Channel is AWGN and 31 bits gold sequence has been used as the spreading codes. Following parameters have been taken for evaluating the performance of a MC-CDMA system.

1. Total number of subcarriers taken is 31.
2. Since the channel is asynchronous (uplink) so every subcarrier go for independent multipath fading.
3. Perfect subcarrier synchronization with no frequency offset is assumed.
4. It is assumed that there is no non-linear distortion.
5. QPSK (quadrature phase shift keying) modulation is used.

In the simulation 10,000 bits per user has been transmitted and these bits are received by different multiuser detectors. A graph is plotted between different values of BER (bit error rate) and different values of Signal to noise ratio (SNR) E_b/N_O. Two different cases are considered for the simulation purpose. In the first case (Case-1), all users are assumed to be received with equal powers at the detector end i.e. there is no Near-Far effect and in the second Case (Case-2) users are received with unequal powers i.e. near-far scenario is considered.

Case-1: As shown in Fig. 12, BER performance of all the detectors is evaluated against Signal to Noise ratio(SNR) i.e. E_b/N(dB).We find that best performance is given by the optimum detector (Maximum-Likelihood) which gives the lowest BER with different values of E_b/N(dB), but it takes 2^K number of iterations. Among the suboptimal detectors, linear detectors (MMSE and decorrelator) gives near optimal performance but at the same time they take only K^2 number of iterations which is much lesser than optimal detector. Decorrelator detector can be termed as a special case of MMSE detector as it does not eliminate background noise as noise variance (σ) is zero in this case. So performance of MMSE detector equals to matched filter detector when noise is large i.e. at low SNR (E_b/N) values, but its performance approaches to that of decorrelator detector when noise is very low i.e. at high SNR (E_b/N) values. In between low and high SNR(E_b/N), BER performance of MMSE detector is slightly better than decorrelator. In case of non-linear PIC detector perform better than SIC in equal power scenario but computational complexity of PIC is more than SIC. Single user detector (matched filter detector) performs poorly in comparison with all other MUD detectors because it could not eliminate MAI effectively as SNR of different users increases. Table 2, gives the BER of all the detectors for different values of E_b/N(dB) after simulation. It can be analyzed from Table 2, that number of bits in error(out of 10000 bits) is lesser in case of optimum detector for all the values of E_b/N(dB).

Case-2: For a near-far scenario, SIC could be the best choice as it gives best BER performance among all other detectors as shown in Fig.13. Reason for such a performance is obvious as SIC arrange all the detectors in descending order of their power levels and then subtract the MAI of strongest user from MAI of composite signal and this process is repeated for K number of times. So in near-far scenario SIC is way ahead of other detectors as far as BER performance is concerned. Performance of MMSE and Decorrelator is also robust and equal in this case as their BER performance curves are superimposed on each other. PIC detector gives the worst performance in near-far condition. Table 3 gives the idea about error bits for different detectors in case of Near-far condition. It can be seen from the Table 3 that SIC detector has much lesser number of bits in error (out of 10000 bits). SIC detector could be the best choice in near-far scenario.

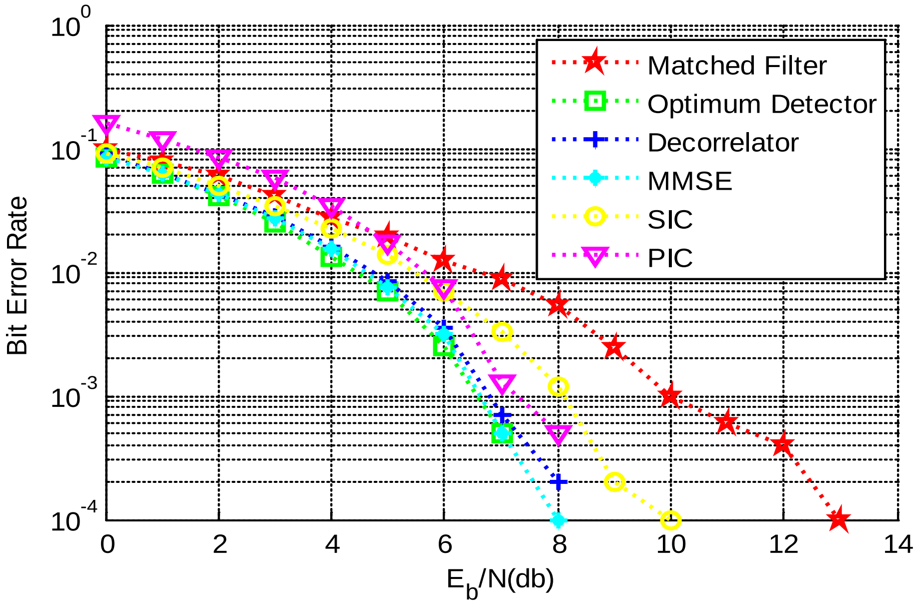

Fig. 12 BER performance under equal power scenario

Table 2: Bits in error (out of 10000) under equal power scenario

SNR	**1dB**	**2dB**	**3dB**	**4dB**	**5dB**	**6dB**	**7Db**
Matched Filter Detector	.0800	.0718	.0654	.0591	.0531	.0471	.0405
Optimum Detector	.1350	.1334	.1326	.1340	.1344	.1356	.1356
Decorrelator Detector	.0590	.0498	.0405	.0334	.0274	.0198	.0146
MMSE Detector	.0583	.0496	.0406	.0334	.0275	.0198	.0146
SIC Detector	.0397.	.0281	.0186	.0106	.0059	.0125	.0014
PIC Detector	.4021	.4010	.4013	.4011	.3993	.3981.	.3960
SNR	**8dB**	**9dB**	**10dB**	**11dB**	**12dB**	**13dB**	**14dB**
Matched Filter Detector	.0338	.0281	.0231	.0184	.0133	.0100	.0075
Optimum Detector	.1359	.1353	.1351	.1341	.1324	.1311	.1301
Decorrelator Detector	.0099.	.0058	.0044	.0020	$8.7500e^{-04}$	$2.500e^{-04}$	0
MMSE Detector	.0098	.0058	.0044	.0020	$8.7500e^{-04}$	$2.500e^{-04}$	0
SIC Detector	$1.2500e^{-04}$.	0	0	0	0	0	0
PIC Detector	.3934	.3885	.3864	.3840	.3820	.3803	.3796

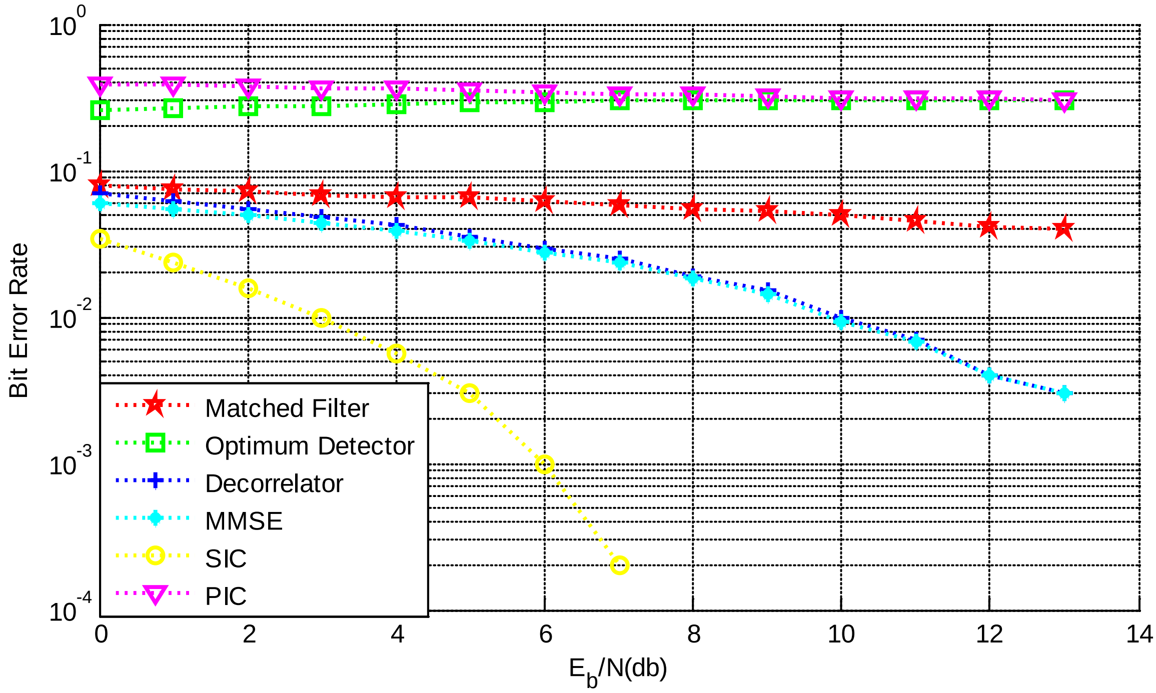

Fig. 13 BER Performance under unequal power (near-far effect) scenario

Table 3: Bits in error (out of 10000) under unequal power (near-far effect) scenario

SNR	**1dB**	**2dB**	**3dB**	**4dB**	**5dB**	**6dB**	**7dB**
Matched Filter Detector	.0901	.0690	.0501	.0339	.0219	.0135	.0077
Optimum Detector	.0823	.0584	.0387	.0237	.0125	.0061	.0025
Decorrelator Detector	.0846	.0613	.0414	.0257	.0140	.0072	.0031
MMSE Detector	.0827	.0606	.0406	.0250	.0138	.0070	.0030
SIC Detector	.0860	.0645	.0449	.0289	.0172	.0100	.0051
PIC Detector	.1187	.0892	.0626	.0400	.0226	.0119	.0052
SNR	**8dB**	**9dB**	**10dB**	**11dB**	**12dB**	**13dB**	**14dB**
Matched Filter Detector	.0039	.0018	5.250e-04	1.500e-04	5.000e-05	0	0
Optimum Detector	8.000e-04	2.125e-04	5.000e-05	0	0	0	0
Decorrelator Detector	1.000e-03	3.500e-04	8.700e-05	1.250e-05	0	0	0
MMSE Detector	9.750e-04	3.250e-04	7.500e-05	1.250e-05	0	0	0
SIC Detector	.0023	.0011	3.000e-04	6.250e-05	1.250e-05	0	0
PIC Detector	1.0000e-03	2.500e-04	2.700e-04	1.75e-05	0	0	0

9. Conclusion

Simulation results show that optimum detector performs well when users are received with equal powers but biggest drawback of optimum detector is its complexity, so it is not preferred for practical implementation. Suboptimal detectors are preferred for this very reason. Linear suboptimal detectors such as MMSE and decorrelator are easy to implement and moreover they provide good BER performance. In near-far scenario, SIC detector gives the best performance. Linear suboptimal detectors are also robust to near-far effect. PIC detector gives good BER performance under equal power control. It is also observed that at high noise level performance of all the detectors is noise-limited but at high SNR values it becomes a MAI-limited problem. As a future work optimization techniques such as Genetic algorithm (GA), Particle swarm optimization (PSO), Ant colony optimization (ACO) etc. can also be used to optimize multiuser detectors in order to reduce complexity. These optimization techniques give near optimal solution with much lesser number of iterations. Different versions of these optimization techniques can be explored to get optimum results.

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