Multiuser Detection Techniques: An Overview [1]

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1 Introduction

The emerging third-generation (3G) wireless communications will support not only voice communications but also high-speed data and multimedia services. In addition, they will also allow subscribers to access several services at once. This means future wireless communications systems should provide a much higher capacity than current systems. Data and multimedia services also have a higher transmission quality requirement. For instance, data usually needs a bit error rate (BER) of better than 10^{-6} as compared with a threshold BER of 10^{-3} for voice. Higher capacity and higher quality requirements pose real challenges for the designing of the 3G wireless systems.

Although various solutions around the world have been proposed which reflect different requirements, there is one common envision that wideband CDMA is the most promising technologies for the next-generation wireless communications. It is well known that the capacity of a CDMA system is limited by multiaccess interference (MAI), caused by the cross-correlation between spreading codes of active users. In the 2nd generation CDMA system like IS-95 [1], single-user detection receiver has been used where MAI is treated as noise. Therefore, when the number of active users in a system becomes large or when the power level of certain users are significantly high, weak users with single-user detectors may lose communication because of the overwhelming MAI. This phenomenon is called near-far problem. Power control is employed in the current 2nd generation CDMA system to mitigate the near-far effect. Ideal power control ensures all users have identical signal power level or signal-to-noise ratio when they arrive at the base-station. Stringent power control plays a important role in practice to guarantee superior performance over existing TDMA and FDMA systems. MAI can be alleviated by multiuser detection. Verdu's original work [2] shows that optimal detection can be achieved by joint sequence decision made from the matched filter outputs of all users. The optimal detector demonstrates a huge capacity improvement over conventional single user detector, however, its complexity grows exponentially with the number of active users which precludes most of its practical application. Motivated by Verdu's work, extensive studies have been carried out in finding suboptimal solutions with significant performance improvement and acceptable complexity. Various suboptimal multi-user detection (MUD) techniques have been proposed in the last 10 years. Unfortunately, either they still have a high complexity or they can only provide a marginal performance improvement over conventional single-user detector in certain circumstances.

In this report, we will present an overview of various MUD techniques proposed. Of particular, we attempt to answer the following questions:

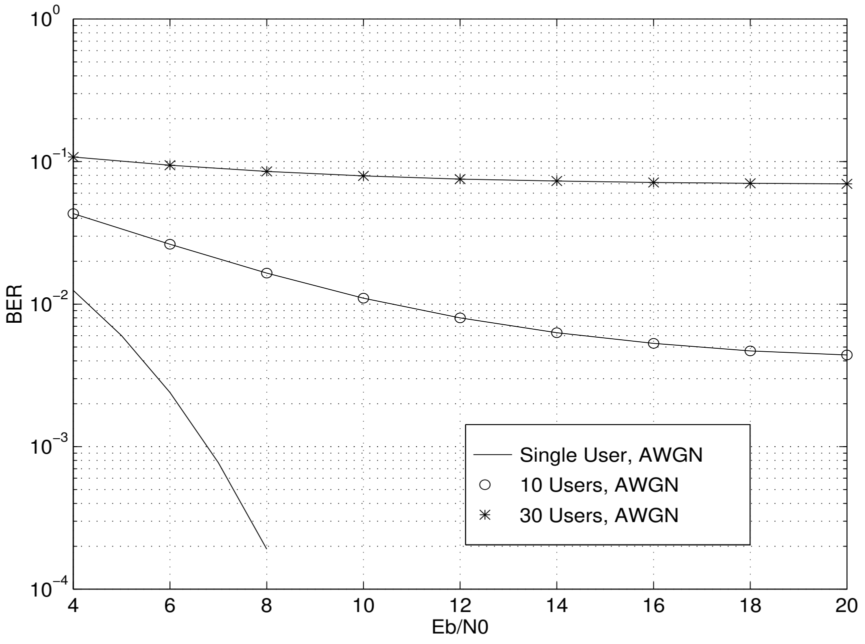
1. Why multiuser detection is so important? How much improvement can be provided by MUD?
2. What are the state-of-the-art MUD techniques?
3. Which detector can provide the best performance? What are their performance under various conditions?
4. Do we still need power control if we have already found a good MUD scheme?
5. What are the implementation issues of MUD?

At the end of the report, we give our conclusions, and suggestions for further research.

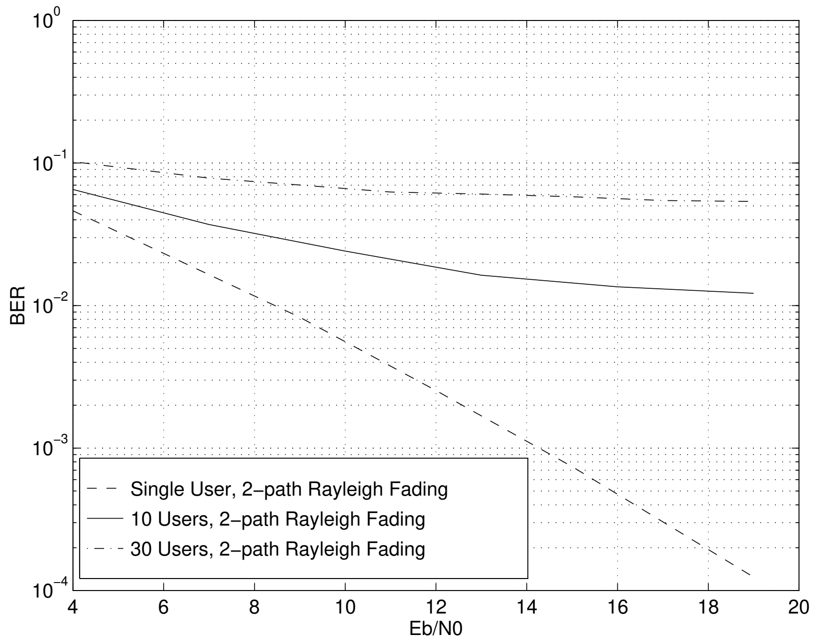
2 Why MUD?

MUD can eliminate MAI caused by other active users in a CDMA system. Verdu has already shown [2] the optimum detector provides a performance that approaches single user bound. In other words, the optimal detector performs as if other users were not exist. Figure 1 shows the bit error rate (BER) versus E_b/N_0 of a CDMA system using QPSK modulation in presence of Additive White Gaussian Noise (AWGN) as well as two-path Rayleigh fading. A processing gain of 64 is used in this system. In general, AWGN channel can be regarded as a special case of perfect power control for any fading channel.

As shown in Figure 1(a), with 10 active users, an E_b/N_0 of 11dB is required to achieve a BER of 0.01. For 30 active users, the BER curve reaches a floor of 0.01 at large E_b/N_0. However, to achieve the same BER performance, the optimum multiuser detector only requires an E_b/N_0 of less than 5dB. A substantial performance improvement is also observed with MUD in a multipath fading channel as plotted in Figure 1(b). Comparing results shown in Figure



(a) AWGN channel



(b) 2-path Rayleigh Fading Channel

Figure 1: BER versus E_b/N_0 for conventional single user detectors

1(a) and Figure 1(b), we find a similar performance in both AWGN and multipath fading channels for the case of 30 active users. In other words, perfect power control is not effective at a relatively high load, however, performance improvement can be achieved with MUD that provides a performance approaching that in a single-user environment.

3 A Survey on Multiuser Detection Techniques

CDMA receivers can be grouped into 2 categories, single-user detectors and multiuser detectors. A hierarchy of various receiver techniques is given in Figure 2.

In CDMA reverse link, the receiver at the base station has a knowledge of all users' spreading codes and transmitted data. Therefore, the receiver can make use of this knowledge to eliminate MAI by performing MUD. In MUD, the optimal detector refers to the maximum likelihood detector suggested by Verdu [2]. As previously mentioned, the optimal detector is too complicated for practical application although it has a excellent performance. For more than a decade, a great effort has been focused on finding suboptimal detectors. Numerous suboptimal approaches have been proposed, most of them can be classified into two categories, namely linear and non-linear multiuser detectors. In linear multiuser detector, a linear transformation is applied to the soft outputs of the conventional detector in order to produce a new set of decision variables with MAI greatly decoupled (or completely decoupled in the decorrelating detectors). Two of the most cited linear multiuser detectors are the decorrelating detector [3] and the MMSE detector [4]. In non-linear multiuser detection which is also called subtractive detection, the interference estimates are generated and then removed from the received signal before detection. Multistage interference cancellation (IC) is the one of the most interests in the non-linear detector category. In multistage IC, the cancellation can be carried out either successively [5, 6] or in parallel [7, 8]. For the rest of the methods, good summaries can be found in [9, 10].

The decorrelating detector offers many desirable features, e.g., it yields an optimal value of near-far resistance performance metric [10] and does not need to estimate the received signal amplitude. It corresponds to a maximum likelihood sequence detector when the signal levels of all users are unknown to the receiver. Its complexity is on the order of $O(K^3)$ where K is the

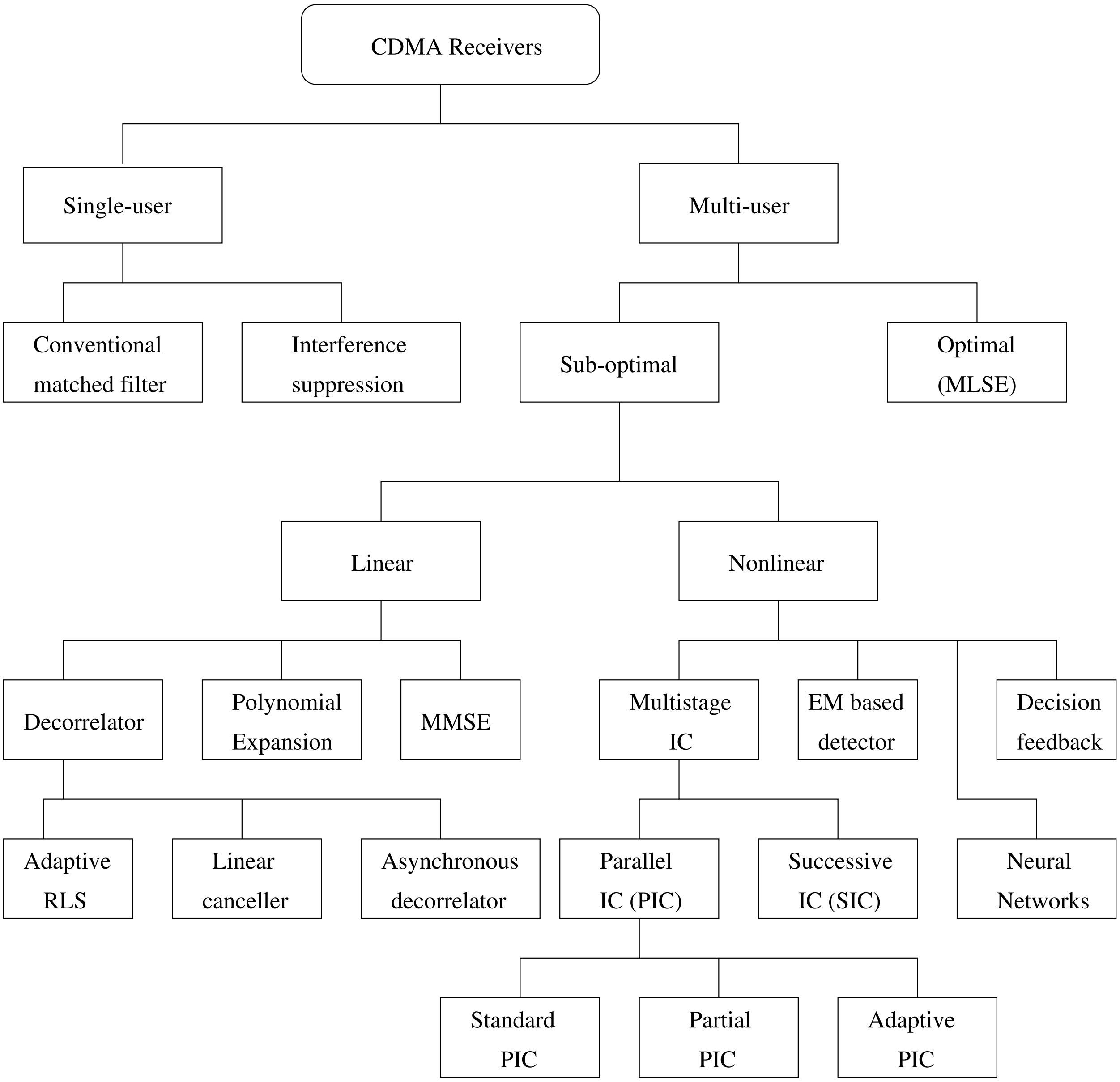


Figure 2: Hierarchy of various CDMA receiver techniques

number of active users, due to the inverse of a cross-correlation matrix. On the other hand, subtractive interference cancellers are much simpler than linear multiuser detectors but have an inferior performance. Another disadvantage of subtractive interference cancellation schemes is that they usually need to estimate the amplitude and carrier phase of all active users.

To solve the multiuser detection dilemma, one can either reduce the complexity of the linear multiuser detectors or improve the performance of the subtractive interference cancellers. For the former, numerous sub-optimal approaches to implement the decorrelating detector have been proposed. These include the attempt to break up the detection problem into more manageable blocks [4, 11, 12, 13, 14, 15] so that the solution to matrix inverse becomes much simpler [16, 17].

For successive interference cancellation (SIC), the performance can be improved by demodulating and canceling each user's signal from the strongest to the weakest according to their received signal power. Performance of such a scheme is analyzed in [6].

In parallel interference cancellation (PIC), performance can be enhanced by introducing multistage [8]. As shown in [18], if the data from all interfering users are known a priori, the optimum decision for the desired user in the sense of maximum-likelihood (ML) should be based on the received signal with all interference canceled. For multistage interference cancellation, the exact knowledge of the interfering bits is unknown, their estimates are used instead, i.e., at the nth stage of cancellation, the detector uses the bit decisions from the $(n-1)$th stage. As the estimates from the previous stages improve, the performance of the multistage PIC can also be improved.

One problem with multistage PIC is that it can not guarantee a performance improvement with more stages. For example, a correct estimation of an interfering user's bit will lead to a successful and perfect removal of this interference. However, when a wrong estimation is applied, the contribution of the interference power will be increased, introducing a further degradation.

In view of the disadvantages associated with the conventional multistage PIC, Divsalar *et al.* [19] suggested a *partial* cancellation of the MAI at each stage, the amount of IC is decided by a weighting factor at each stage for all users. When the weight is properly chosen at each stage, this method can ensure a better performance after the partial interference cancellation.

Since the estimates of the users' data become more reliable when more MAI has been canceled, they propose to increase the weighting factor for each successive stage. Their results show a considerable capacity increase in an AWGN channel.

CDMA forward link is quite different from the reverse link. In the forward link, the mobile station does not have any information on the signal transmitted by other active users. Instead of doing a MUD, the mobile receiver can conduct interference suppression [20, 21], where an adaptive filter is used to minimize the squared error between the transmitted bits and their estimates. When short PN code is employed, this method has the ability to suppress the MAI without any knowledge of other users. Furthermore, with fractional spaced FIR filter, the interference suppression scheme can take the advantage of the cyclo-stationary property thus able to be performed blindly. It is demonstrated in [22] that the interference suppression method can offer considerable performance improvement over conventional single user matched-filter detector.

4 Which Detector? – Performance Comparison

4.1 Interference cancellation versus. linear detection

Linear multiuser detectors use linear transformation to decouple the MAI contained in the output of each user's matched filter. Generally speaking, linear detectors are superior to the interference cancellers in terms of combating MAI. Decorrelating and MMSE detectors are the two well-known linear detectors. Decorrelating detector can completely eliminate the impact of MAI at the expense of increased noise. MMSE detector can also significantly reduce the MAI effect while taking the background noise into consideration.

Direct performance comparison between linear detectors and interference cancellation detectors can be found in some recent publications [23, 24].

Performance of SIC, partial PIC, decorrelating and MMSE detectors are compared in [23] for various conditions such as perfect power control, single path Rayleigh fading and 2-path frequency selective Rayleigh fading, the processing gain is 31 in their system. In the following, we summarize their results.

1. When the system has perfect power control, partial PIC has the best performance. MMSE and decorrelating detectors have similar performance, e.g., for BER of 10^{-3} and $E_b/N_0 =$ 8dB, MMSE and decorrelating detectors both have a capacity of 15 users, while partial PIC can accommodate 20 users.

2. In single path flat Rayleigh fading channel, the BER performance versus E_b/N_0 is investigated for the above 4 methods with 10 active users. It is shown, when $E_b/N_0 > 15$dB, the linear detectors begin to have their advantages.

3. For 2-path frequency selective Rayleigh fading channel, results similar to the single path case are observed. However, the performance gap between linear detectors and IC detectors becomes more obvious when $E_b/N_0 > 15$dB than in the single path situation.

In Juntti *et al.*'s more recent paper [24], performance of PIC and decorrelating detectors have been compared for BPSK CDMA system over multipath Rayleigh fading channels. A Gold PN sequences of length 31 is employed, furthermore, decision-directed channel estimation is considered. They have investigated two situations namely equal transmission power as well as near-far problem. In equal transmission power case, all users have identical transmission energies, while in near-far problem, one third of the users are 10dB stronger than the other, the desired user belongs to the weaker group. Their simulation results indicate that from low to moderate SNR, PIC outperforms the decorrelating. The decorrelating is only superior to PIC under severe near-far problem at high SNR. For both methods, there's a big gap to reach the single user bound.

4.2 SIC or PIC

The SIC detector takes a serial approach to cancel interference. At each stage of SIC, only one user's signal is removed from the overall received signal, so that the remaining user see less MAI in the next cancellation. On the other hand, a PIC detector estimates and subtracts out all the MAI for each user in parallel. The advantages of SIC detector is that it requires only minimum amount of additional complexity. However, canceling one user in SIC will cause one bit delay, when the number of users is large, the excessive delay will become unacceptable. In general, PIC will cause much less delay compared SIC, its complexity is higher than SIC. Performance comparison between various SIC and PIC schemes can be found in the [25, 23, 18].

In [25], performance of an SIC scheme is compared with standard multistage PIC detector for asynchronous CDMA system with BPSK modulation and coherent detection. In the SIC approach, the cancellation is conducted in an order from the strongest to the weakest according to the users' power levels. Processing gain used in their system is 31, there is no AWGN. Simulation results show

- With perfect power control, one-stage PIC can support 36 users, while the capacity of SIC is 18 for BER of 10^{-3}, Meanwhile, one additional stages in PIC introduces further improvement.

- Without power control, SIC scheme is superior to PIC. For BER of 10^{-3}, 2-stage PIC can accommodate 16 users while SIC can support 25 users.

Divsalar *et al.* point out in [18] that the PIC detector is equivalent to a maximum likelihood sequence detector if all the interference is known *a priori*. In practice, the exact knowledge of the interference is not available, their estimates are used instead. Since the estimations are not perfect, especially when the system load is high, complete cancellation of the estimated interference in conventional PIC will cause performance degradation. They suggest partial removal of the estimated interference by weighting the interference estimates by a factor with value in (0, 1) at each stage. Similar idea can also be found in [23].

Performance of partial PIC is compared with SIC in [23] over single path and multipath Rayleigh fading channel. They considered a system similar to that in [25], but AWGN is taken into account. The results are summarized in the following

- With perfect power control, two-stage partial PIC is considerably better than SIC discussed in [25]. For E_b/N_0 = 8dB and BER of 10^{-3}, SIC has a capacity of 6 users, while two-stage partial PIC can support 20 users.

- In a single path flat Rayleigh fading as well as 2-path frequency selective Rayleigh fading channel, 2-stage partial PIC and SIC have very close performance when the system has 10 users and E_b/N_0 is within 0dB to 10dB.

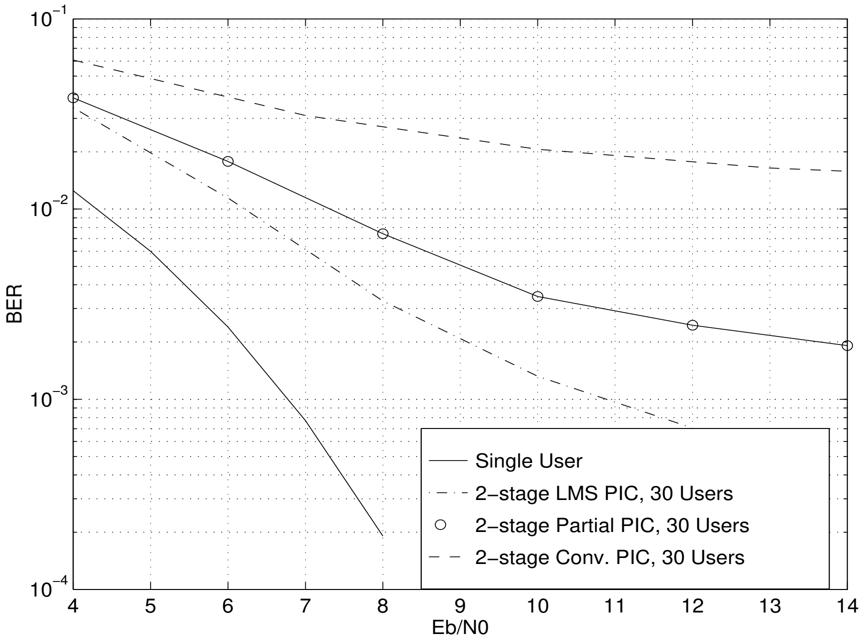


Figure 3: Performance comparison of various PIC schemes over AWGN channel

4.3 Our Research Results

PIC has the potential for further performance improvement if certain knowledge of the MAI is available. The partial PIC scheme [19] is only a compromise between complete removal of MAI and reduce the cost of wrong IC. Based on the partial PIC method, we have proposed a new scheme called adaptive multistage PIC. In the proposed approach a set of weights are obtained by an LMS algorithm such that the mean square error between the received signal and its estimate is minimized.

We have carried out a comparison study with various PIC schemes in a system described in section 2. Results obtained from simulation are presented in the following.

In AWGN channel, or in other words, when the system has perfect power control, 3 PIC methods have been compared. As can be seen in Figure 3, the proposed 2-stage LMS PIC can provide 1dB gain over the 2-stage partial PIC at BER of 0.01 when the system has 30 users. At BER of $2\text{x}10^{-3}$, the gain is about 4.5dB.

Performance comparison in a 2-path Rayleigh fading channel is depicted in Figure 4. For system with 30 users we can see that all three 3 methods have very similar performance which is very close to the single user bound in the 2-path Rayleigh fading channel.

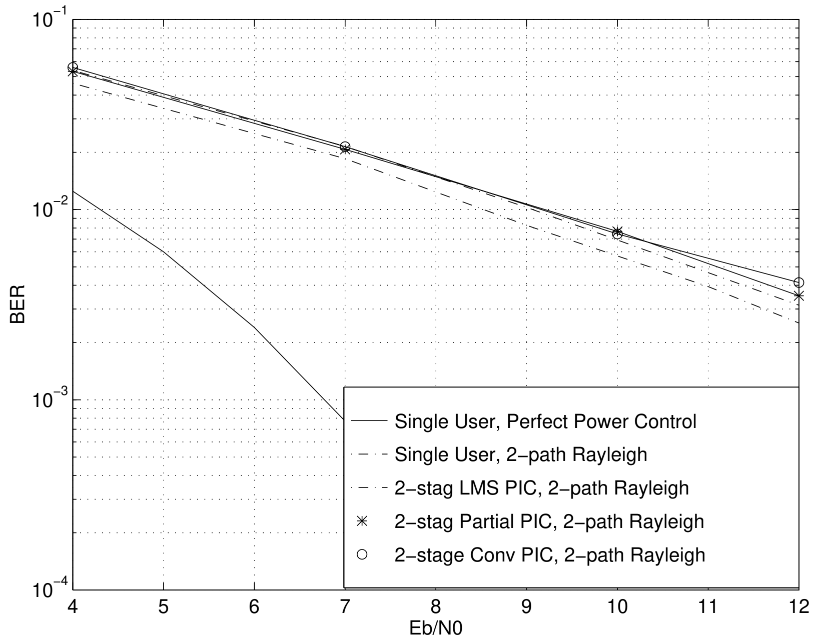


Figure 4: Performance comparison of various PIC schemes over a 2-path Rayleigh fading channel

5 Power Control and Multiuser Detection

Power control will ensure all users to have the same power level when their signal arrives at the base-station. The successful deployment of the second generation CDMA system is greatly due to the stringent power control. However, as we have already mentioned in section 2, CDMA system will not benefit from power control when the system load is high. There is a misunderstanding that with a good MUD scheme power control is no longer necessary. To be more specific, let us look at Figure 4. Although, the proposed LMS PIC method can provide near single user bound performance in a 2-path Rayleigh fading environment when the system has 30 users, we noticed that there is a big gap to reach the single user bound in AWGN channel. In other words, power control and MUD together will give a significantly better performance than MUD alone. For the case given in Figure 4, assume the multiuser detector is the optimal one, perfect power control will introduce a 4dB gain at BER of 0.01 compared that if the optimal detector works in the 2-path Rayleigh fading channel without any power control. For the proposed 2-stage LMS detector, with perfect power control, there is nearly 3dB gain for BER of 0.01. Therefore, we can conclude that power control performs a different role when used with MUD.

6 Implementation Issues

Multiuser detection has been a hot topic in CDMA communication since early 90s'. For more than 10 years since the introduction of the optimal detector [2], numerous methods have been proposed and hundreds of papers have been published in this area. In addition, hardware implementations of MUD receiver prototype have been reported in [26, 27], yet to the best of our knowledge, multiuser detector is not available in commercial products. Besides the performance improvement, complexity as well as the robustness of the multiuser detectors are the two main issues in implementation. In the following of this section, we will give a summary on these two topics.

6.1 Complexity

There is a good summary in [23] on the complexity of decorrelating detector, SIC and PIC detectors. The complexity is often measured by number of floating point operations (flop) required. In the following, we will present the complexity of some of the popular multiuser detection methods. The quantity of flops is defined by the number of users K, the number of path tracked by RAKE receiver L, processing gain N, the number of stages S and the frame length N_f.

Decorrelating detector has a very high computational complexity. In asynchronous multipath fading channel, the complexity of a matrix-inverse decorrelating detector is on the order of $N_f^2(LK)^3$ [23] (this value is $N_f(LK)^3$ in [17]). Significant reduction in complexity is reported in [9] by introducing a sliding window in the decorrelating. The complexity is reduced to the order of $N_f(LK)^2$. Most recently, Juntti *et al.* have proposed an iterative method [17] to implement decorrelating detector as well as MMSE detector. The complexity is reduced to $O(N_fK^2)$ in asynchronous AWGN channel.

On the other hand, SIC is probably the simplest way to implement MUD. The additional complexity over single user receiver stems from channel estimation in regeneration MAI, re-spreading and MAI cancellation. It is shown in [23] the complexity of a SIC detector is only

$O(LNK)$.

Usually, PIC is supposed to be more complicated than SIC, because each user has to cancel all the MAI at each stage. When doing in this manner, the complexity of multistage PIC is $O(K^2)$ [26]. It is also indicated in [26] that dramatic complexity reduction can be achieved by computing the residual MAI first, followed by calculating a new decision statistic which is derived from the residual MAI and a correction factor. Since the residual MAI is common to all users, it only need to be computed once per stage, thus greatly reduces the computation. The overall complexity of this method is only $O(LSKN)$ which is comparable to that of SIC.

6.2 Robustness

Most of the discussions and analysis on MUD assume certain ideal conditions. In reality, these detectors will work in an environment subject to phase estimation error, time jittering and imperfect amplitude estimation in re-creating MAI and bandlimit etc. It is desirable to know whether the existing MUD methods will still be able to provide significant gains over conventional detector? Unfortunate and fortunate, few researchers have been undertaken studies on this topic.

Impact of tracking (including frequency, amplitude phase and timing) errors on the performance of decorrelating detector was analyzed in [28]. The tracking error is assumed to be Gaussian distributed. Performance of decorrelating detector versus the standard deviation of tracking error was studied by simulations. For a system of 3 active users employing Gold codes with length 31, the authors have shown that the decorrelating detector is quite sensitive to tracking errors.

A simple analysis on tracking error for a coherent BPSK system with SIC was reported in [29]. Each user is assigned a PN code of length 31, perfect power control is assumed. Simulation results show some degree of robustness, the SIC scheme retains its superiority over conventional single user detector. Consistent results have also been reported for SIC over one-path Rayleigh fading channel [30]. In a case, where the mobile speed is 100km/h, the system has a tight power control (1dB standard deviation with respect to nominal received power), an error of 5% in chip synchronization does not cause significant degradation in BER performance. An extensive study of phase and timing errors on the performance of PIC scheme was given in [31],

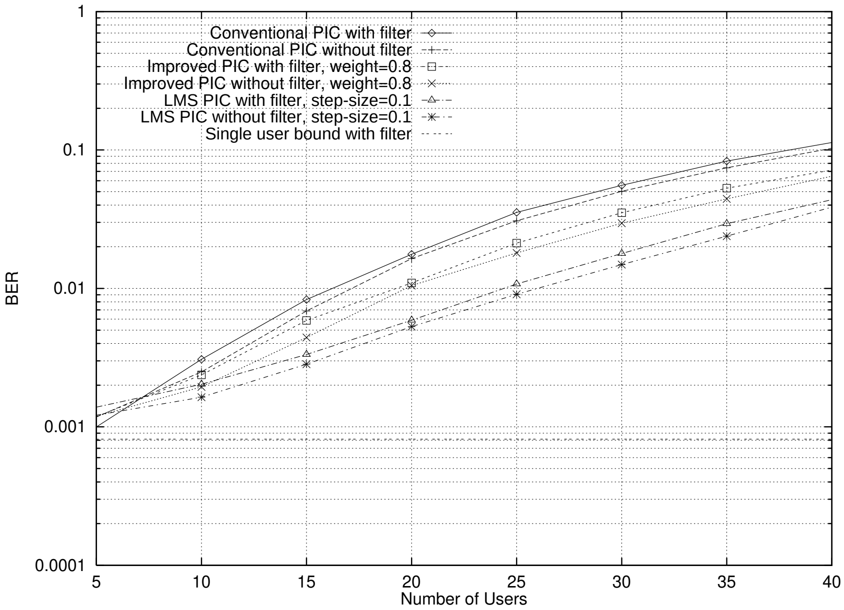


Figure 5: Effect of bandlimit on the performance of PIC

where BPSK system with coherent demodulation was investigated, the processing gain is 31 and $E_b/N_0 = 8$dB. For timing errors, they studied the case with 10 users and the timing errors vary from 0 to $0.4T_c$, where T_c is the duration of a chip. Both simulation and theoretical results show that as timing errors increase, the gain due to interference cancellation is reduced. However, for errors up to $0.4T_c$, the multistage approach still outperforms a conventional receiver. The impact of timing error on capacity was also studied for a system with a processing gain of 128. Theoretically, an ideal two-stage PIC cancellation can support approximately 160 users at BER of 0.01, as opposed to 40 users for the ideal conventional single user detector. With timing error equals to $0.2T_C$, the 2-stage PIC detector still has a capacity of 75 users, while the capacity of the single user detector drops to 30 users. Their research on phase errors indicates phase errors will too degrade the performance as well as performance gains, however, the multistage PIC approach still outperforms conventional single user detector in the presence of phase errors. Phase errors are less critical than timing errors. Recently, we have investigated the effect of limited bandwidth on the performance of multiuser detectors. In a real system, a low-pass filter must be used to limit the bandwidth of the transmitted signal. In our study a root raised cosine FIR filter with roll-off factor 0.2 was employed (the system structure as well as the filter parameters can be found in [32]). Results for AWGN channel are plotted in Figure 5.

As demonstrated in Figure 5, the band-limitation will slightly degrade the performance of the PIC detectors.

7 Conclusions:

In this report, we presented a survey on multiuser detection techniques. The four most discussed multiuser detection structures namely decorrelating, MMSE, SIC and PIC have been compared in terms of BER performance, complexity and robustness. Meanwhile, we have also pointed out the different role power control plays in the presence of MUD. Through our investigation, we can draw the following conclusions:

- Linear detectors are not necessarily to be superior than subtractive detectors. Results from different sources indicate that in a more practical situation (low SNR, moderate near-far problem), multistage PIC will outperform decorrelating detector.

- Interference cancellation methods have a clear edge in terms of complexity. Complexity of linear detectors are one or two orders of magnitude higher than IC approaches. Within the IC category, each stage of a PIC detector is slightly higher than SIC detector.

- Decorrelating detector is very sensitive to timing errors, whereas PIC and SIC are fairly robust against timing errors as well as imperfect phase estimation. However, IC methods are more vulnerable to amplitude estimation error than decorrelating detector.

- Even with a good MUD technique, power control is still valuable for future wideband CDMA system.

In short, we believe interference cancellation, especially multistage PIC is the most promising MUD techniques for the coming 3G wideband CDMA system. Meanwhile, the proposed adaptive multistage PIC method provides a very attractive solution that deserves a further investigation.

We suggest the following topics for further research:

1. Impact of power control on the performance of MUD. As previously mentioned, perfect power control can improve the single user bound in a multipath fading channel to that

of an AWGN channel, this improvement is usually considerable. To the best of our knowledge, when the power control is non-ideal, the power distribution model, single user bound as well as the performance of MUD are not fully investigated. Therefore, it is necessary to continue our research in this area, and hopefully, through our study we can answer which MUD method has the best performance plus how stringent power control is required to make full use of a particular detection method.

2. Practical considerations of the adaptive multistage PIC method. These include to study the effect of timing errors, imperfect phase and amplitude estimations and quantization etc.

3. Interference suppression. Our previous effort was concentrated on MUD in CDMA reverse link. For forward link, interference suppression has been suggested which is essentially a single user detector. Although its performance has been studied by some researchers, we still have a lot of interesting to know whether there is a possibility for improvement, what are the implementation issues and so on.

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