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Receivers for Multirate CDMA Systems

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ABSTRACT

The scope of this report is to give an overview of the receivers used in multirate CDMA systems. First, some background is given. Thereafter, different means to provide multirate in CDMA systems are presented. In the next chapter, some examples of multirate receivers are covered. The final two chapters present solutions proposed for 3rd generation standards and draw conclusions about the subject.

1. INTRODUCTION

Multirate receivers is a very interesting topic at the moment since the 3rd generation network standardisation work is going on and the development work of future systems is proceeding very fast at the moment. 3rd generation networks are required to support variable bitrates. As many of the most promising candidates for 3rd generation standards are CDMA systems the multirate receiver topic is very current.

In this course various presentations have covered different parts of CDMA systems. The basic information of CDMA cellular systems can be read from these presentations, e.g. [1]. For a more in-depth description there are available various books which cover spread spectrum cellular systems, e.g. [2], [3].

2. CDMA MULTIRATE TRANSMISSION

There are various ways how multirate transmission can be carried out in a CDMA system. For instance, it is possible to change chip rate [7], modulation [4], processing gain [5], and the number of parallel channels [6]. Of course, these alternatives can be combined, e.g. spreading factor and the number of parallel channels can be changed at the same time. All solutions have different advantages and disadvantages. In the following, a short description of the characteristics of some potential alternatives is presented. This description is based on the comparisons presented in [4] and [8].

2.1 Multi-Modulation Systems

A multi-modulation system where all users have the same symbol rate and processing gain is not optimal way to implement multi-rate systems. First of all it would be difficult to implement many data rates by only changing modulation. Further, if it is assumed that all the users have the same signal-to-noise ratio per bit the transmitted powers are different for different rates. As the spreading code is the same for different users near-far-effects will arise. If on the other hand all users transmit at the same power the performance of high data rate users will degrade because of the lower E_b/N_0. For BPSK and QPSK modulation everything works fine but for higher modulation schemes the energy per bit is so small that the bit error probability increases strongly.

2.2 Multi Chip Rate Systems

In a multi chip rate system users have different bandwidths and the system is thus partly frequency division multiplexed. For low bandwidth channels the performance of RAKE receiver decreases because the number of multipaths that can be separated decreases giving less diversity. Also different frequencies interfere with each other because of the sideslopes of the subsystems. Consequently, in a multipath environment the capacity of multi chip rate scheme is likely to be below a multi-channel or variable spreading factor system. Despite these disadvantages multi chip rate scheme can be used, for instance, to create several layers to a network or to provide certain services with a certain chip rate. It is an unlikely solution to change the chip rate during a call to provide variable bitrate service.

2.3 Variable Spreading Code Systems

In a variable spreading factor system different data rates can be easily generated by altering the spreading code without touching the chip rate, modulation or coding. For high bitrates the processing gain is small which decreases the protection against the interference. Another problem is that it may be difficult to find orthogonal codes for all data rates in the forward link. Orthogonal codes can be found only if the data rates of all connections are constrained to $R=R_C/2^n$, where n=0,1,...and R_C is the chip rate. If it is not possible to have orthogonal codes inter channel interference will increase. Despite the problems caused by the short processing gain for high bitrate services variable spreading factor scheme is a very potential solution for providing multi rate services. Since the transmission is carried out only on one channel the complexity of RAKE receiver remains low. In addition, the requirements for the power amplifier are not as strict as in the multi channel case.

2.4 Multi-Channel Systems

In a multi-channel system it is possible to provide different bitrates by allocating several constant bitrate channels for the same user. Under the circumstances, how many different data rates can be supported depends on the definition of the basic bitrate. The disadvantage of this solution is that the more bitrates are needed the more complex will the receiver structure be. Since all channels have the same, quite high, processing gain the suppression of intra cell interference is good. The inter symbol interference received from one channel is in this case much smaller than when variable processing gain is used for high bitrate transmission. However, the interference is received from all the channels that are used for transmission. Thus, the overall inter symbol interference is the same both in multi channel and in variable processing gain alternatives.

The definite advantage for multi channel solution is that in the forward link it is relatively easy to find orthogonal codes. Because multiple channels give rise to large amplitude variations the requirements for the power amplifier are much more strict than in the variable spreading factor solution. This is a problem if the number of parallel channels is large. Especially problematic this solution is in the reverse link direction where the linearity of the mobile amplifier should be guaranteed. Another problem is that with M channels M RAKE receivers are needed for each connection. However, because of the interference suppression provided by the longer spreading code the complexity of these RAKE receivers can be lower than the complexity of the RAKE receiver in the variable spreading factor solution.

2.5 Comparison

What is the best scheme for multirate transmission depends on many other things than only the performance. It seems that multi channel and variable spreading factor solutions are preferred to the multi modulation and multi chip rate schemes but which one of the two is better is a more difficult question. Multi channel solution can provide orthogonal channels in the forward link which is more difficult for the variable spreading factor solution. On the other hand, variable spreading factor solution works with one RAKE receiver. In the multi channel case as many RAKE receivers are needed as there are channels. However, these receivers can be simple because of the higher processing gain in each channel. In addition to the high complexity of the receiver another severe problem for the multi channel solution is the requirement for linear amplifier, especially in the reverse link direction. The right choice depends, beside the above things, also on the power control implementation, code allocation and such things which must be considered when the decision of the technique is made.

3. MULTIRATE RECEIVERS

In this chapter three articles of receivers used in multirate systems are referred. It can be noticed that actually there aren’t such a thing as a multirate receiver but different types of receivers have been used in CDMA systems where multiple data rates are supported. The multirate concept introduces certain new characteristics but mainly the receivers are as in traditional CDMA systems.

3.1 Multiuser Detection for Multirate CDMA Communications

Multiuser detection (MUD) is a one way to increase information capacity in a CDMA system. In a conventional CDMA system where all users transmit with a low power level MUD is not essential. This is because pseudo-noise codes provide sufficient protection against the interference. In addition, the number of simultaneous users is so high that the complexity of MUD is excessively high. Consequently, multiuser detection is not used in 2nd generation CDMA systems like IS-95. In 3rd generation systems where simultaneous mixed services are to be supported MUD or interference cancellation would provide more benefits but still at the moment the complexity of these schemes is too high to be considered as an alternative. Under the circumstances, they remain as receiver structures of the future (4th generation ??). In few years the development of DSPs is likely to be so fast that the complexity problem can be solved. In a high bitrate network the number of concurrent users is probably relatively low which further decreases the complexity of MUD.

In [11] a multiuser detector concept for multirate CDMA communication is presented. The concept maintains fixed chip rate and symbol alphabet while the processing gain is changed to support different bitrates. In order to maintain the required symbol energy higher bitrate channels are transmitted with higher power. This gives rise to near-far problems which are solved with MUD.

Consider a high capacity channel where K_k users transmit at M_k symbol rate compared to the minimum rate R. Assume that there are K different transmission rates the total information capacity is:

$$R\tilde{K} = R\sum_{k=1}^{K} K_k M_k \qquad (1)$$

It can be noticed that it is possible to attain the same information capacity either by accommodating $\tilde{K}$ users each transmitting with the minimum rate or by allocating the transmission rate M_k for K_k users where $K_k \in [1,K]$. Thus it is possible to design a receiver for $\tilde{K}$ low bitrate users and to use that for multirate reception of smaller amount of high bitrate users provided that the maximum capacity is not exceeded. Assume a multiuser receiver where there are $\tilde{K}$ channels (or virtual low bitrate users). In this system user k accommodates information channels $1+\sum_{k'=1}^{k-1} M_{k'}$ to $\sum_{k'=1}^{k} M_{k'}$. Assuming that delays are known signal can be despread by:

$$z_{k,l}^{(i)} = \int_{iT+\tau_{k,l}}^{(i+1)T+\tau_{k,l}} r(t) s_k^*(t-\tau_{k,l} - iT)dt \qquad (2)$$

where k=1,..., $\tilde{K}$. The outputs of *k*th user's matched filters are collected to the vector $z_k^{(i)} = (z_{k,1}^{(i)},\dots,z_{k,L}^{(i)})$, see figure 1. Similarly the outputs of all $\tilde{K}$ users are put to the vector $z^{(i)} = (z_1^{(i)},\dots,z_{\tilde{K}}^{(i)})$. The sequence of matched filter outputs is denoted as $z = (z^{(-P)},\dots,z^{(P)})^T$. The amplitude related to the *i*th symbol of *k*th user's *l*th path is denoted as $\alpha_{k,l}^{(i)}$. Accordingly the amplitudes of the *k*th user's channel coefficients at the *i*th symbol interval are denoted as $\alpha_k^{(i)} = (\alpha_{k,1}^{(i)},\dots,\alpha_{k,L}^{(i)})^T$. The matrix of the received signal amplitudes for all users $\tilde{K}$ is defined as $A^{(i)} = diag(\alpha_1^{(i)},\dots,\alpha_{\tilde{K}}^{(i)})$. In order to define a multiuser receiver we still need a correlation matrix of the received signals. The correlation between *k*th user's *l*th multipath component and *k*th user's *l*th multipath component is defined as:

$$\left[R_{k,k'}^{(n)}\right]_{l,l'} = \int_{-\infty}^{\infty} s_k(t-\tau_{k,l}) s_{k'}^*(t-\tau_{k',l'} - nT)dt \qquad (3)$$

and the following matrices:

$$R^{(n)} = \begin{pmatrix} R_{1,1}^{(n)} & . & . & . & R_{1,\tilde{K}}^{(n)} \\ . & . & & & . \\ . & & . & & . \\ . & & & . & . \\ R_{\tilde{K},1}^{(n)} & & & & R_{\tilde{K},\tilde{K}}^{(n)} \end{pmatrix} \qquad (4)$$

$$R_P = \begin{pmatrix} R^{(0)} & . & . & . & R^{(-2P)} \\ . & . & & & . \\ . & & . & & . \\ . & & & . & . \\ R^{(2P)} & & & & R^{(0)} \end{pmatrix} \qquad (5)$$

Matrix R_P consists of the correlations affecting the despread signal over 2P+1 neighbouring symbol intervals. The despread signal is given now by:

$$z = R_P A b + n \quad (6)$$

where $A=\mathrm{diag}(A^{(-P)},...,A^{(P)})$, $b=(b^{(-P)},...,b^{(P)})^T$, $b^{(i)}=(b_1^{(i)}1^T,...,b_K^{(i)}1^T)$. Here $1^T=(1,...,1)$ is a L vector.

The equation 6 can be interpreted so that the output vector from the matched filters is equivalent to the multiplication of the correlation matrix times the amplitude matrix times the transmitted symbol vector plus noise. The problem is to estimate the transmitted symbols. This is equivalent to the following minimisation problem.

$$b_{opt} = \arg\min_{b} \left\| z - R_P A b \right\|^2_{R^{-1}} \qquad (7)$$

where $\|y\|^2_C = y^H C y$ and C is a weighting matrix. It can be easily seen that the problem is in practice difficult to solve. The complexity of the optimum solution depends exponentially on the number of paths and the number of users. However, in the case of multirate transmission with fixed number of virtual low bitrate users a smaller number of actual high bitrate users is supported. Consequently, the complexity of the multiuser detector per decoded bit decreases considerably. Interested readers may refer to [9] for a formulation of an iterative solution of equation 7. Authors have also simulated the proposed multiuser detector concept. They conclude that when different data rates coexist in a channel the performance of a normal RAKE receiver is inadequate. Multiuser detector makes the situation much more robust and increases the system capacity. Furthermore, the users of lower data rates show worse performance. This follows from the fact that the high data rate users have more power and thus get better channel estimates.

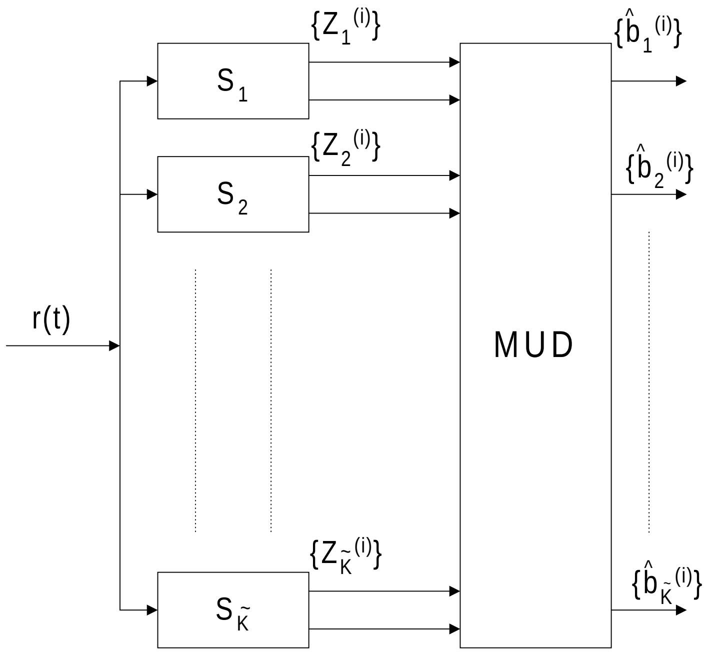

Figure 1. Multiuser receiver for K users [11].

3.2 Optimal Power Control Law for Multi-Media Multi-Rate CDMA Systems

Power control is a central part of a CDMA system. It is needed to mitigate near-far effects and to guarantee sufficient E_b/N_0 level in the receiver. Traditional approach to the problem has been to adjust the transmission power according to the distance to the base station and the interference level to meet the bit error requirements. In [10] a special power control law for multi-media multi-rate CDMA systems has been derived. The motivation behind the work has been to maximise the system capacity and to minimise the power consumption while guaranteeing sufficient BER performance.

In the paper, authors first present a channel model and a receiver model. Thereafter, a BER probability function for fading channel is derived using Gaussian approximation. An enhanced probability function is presented to improve the reliability of the BER model in a multirate environment where users' processing gains can be different and some of the processing gains can be very small. As the central performance criteria is BER performance convolutional coding and Viterbi decoding are introduced to obtain better performance. The power control function is then derived by defining different BER targets for different bit rates and optimising two objective functions.

Objective 1, maximise capacity:

$$\max J_1 = \max_{g_i()} \left\{ \sum_i w_i K_i \right\}$$

s.t. $\qquad P_e^{(i)}(r_{ik}) \le Q_i \,,\ \forall\ i,k$

$$0 \le g_i(r_{ik}) \le 1 \ , \ \forall \ i,k$$
$$K_i \ge 1$$

where w_i = relative weight of rate i, K_i = number of active mobiles with rate i, $g_i()$=power level as a proportion from the maximum power, $P_e^{(i)}(r_{ik})$=bit error probability of user k with rate i, at distance r from base station, Q_i= quality of service requirement (BER) for the rate i.

Objective 2, minimise the sum of average transmission powers:

$$\min J_2 = \min_{g_i()} \left\{ E\left[\sum_i g_i(r) \right] \right\}$$

s.t.
$$P_e^{(i)}(r_{ik}) \le Q_i \ , \ \forall \ i,k$$
$$0 \le g_i(r_{ik}) \le 1 \ , \ \forall \ i,k$$

The optimisation is carried out using dynamic programming and the result is presented as a discrete power control law. The resulting power control law is a function of distance, transmission rate and the interference level (number of simultaneous users).

$$g_i(r_{ik}) = \gamma_0 r_{ik}^{\eta}$$

where g_i = relative proportion of the maximum power, r_{ik} = distance of user k form the base station, η = propagation exponent, γ_0 = constant depending on the quality requirement (BER) of the service.

Authors present simulation results which show that their power control law increases the system capacity (the number of served users). They conclude that since different services have different quality of service requirements mobiles should use the minimum transmission power to meet the BER target. There is nothing especial in this result. In a cellular system one should always avoid using more power than is needed.

3.3 Multistage Interference Cancellation in Multirate DS/CDMA on a Mobile Radio Channel

This chapter follows the analysis presented in [12]. In the article the main emphasis is on the development of a new interference cancellation scheme which is then applied to a multi rate concept.

A conventional multiuser detector consists of a bank of matched filters. This structure is optimal in a single user channel corrupted only by white Gaussian noise. The presence of multiple users in the system often introduces multiple access interference (MAI) which may lead to irreducible error probability. MAI usually rises in an asynchronous system where different propagation delays increase the gross-correlation between the spreading sequences. Another issue which decreases the performance is the near-far effect. In the reverse link, the signals of different users are received with different powers. Traditional way to mitigate this problem is power control. Another technique which has been studied extensively is multiuser detection, which can take care of both the near-far effect and the MAI. In [12] the subject has been multiuser detection which applies interference cancellation. To be precise a multistage interference cancellation scheme in a multipath environment for multirate CDMA systems has been studied. In the paper a modified RAKE receiver is used to get the advantage of diversity and a hybrid IC scheme combining both the decision directed IC and the non decision directed IC is presented.

Consider a system where there are K users and each user's signal is received through P paths. Further, the modulation is a square lattice QAM. The received signal is the sum of all the reflections embedded in Gaussian noise. Consequently, the received composite signal can be represented as:

$$r(t) = \sum_{k=1}^{K}\sum_{p=1}^{P}\alpha_{k,p}\sqrt{\frac{2E_0}{T}}d_k^I(t-\tau_{k,p})c_k^I(t-\tau_{k,p})\cos(\omega_C t+\phi_{k,p}) +$$

$$\alpha_{k,p}\sqrt{\frac{2E_0}{T}}d_k^Q(t-\tau_{k,p})c_k^Q(t-\tau_{k,p})\sin(\omega_C t+\phi_{k,p}) + n(t) \qquad (1)$$

where $d_k^{I/Q}(t)$ are the in-phase and quadrature information bearing signals of user k, $\alpha_{k,p}$ is the channel gain of the *k*th user's *p*th path, $c_k^{I/Q}$ are *k*th user's signature sequences for in-phase and quadrature branches, $\tau_{k,p}$ is the time delay corresponding *k*th user's *p*th path, $\phi_{k,p}$ is the phase of *k*th user's *p*th path.

In a basic multistage interference cancellator of a M-ary QAM the receiver consists of a bank of filters matched to the I and Q spreading sequences of each user. Initially the users are ranked in decreasing order of their respective received signal power. The output of the matched filter of the strongest signal is used to estimate the user's baseband signal which is then cancelled from the composite signal, see figure 2. In the figure c_k denotes the complex sum of c_k^I and c_k^Q. r^i_{k-1} is the composite base band signal after cancelation of user k-1. Superscript i defines the stage of cancellator. d_k^i is the estimated signal of user k on stage i. The procedure starts with the cancellation of the strongest user after which the second strongest user is cancelled and so on. Because the cancellation is not perfect in each cancellation some noise is added to the remaining composite signal. This noise is due to multiple access interference and Gaussian noise existing in the original signal.

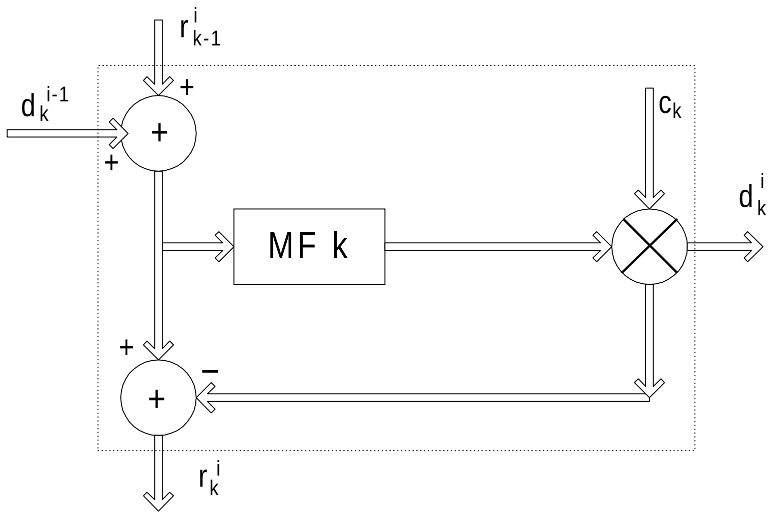

Figure 2 Interference cancellation unit [12].

When there are more than one stages some more MAI can be cancelled from the system and the estimates can be improved by this means. This happens by adding the estimated signal of the previous stage to the composite signal and using the output of a matched filter to obtain a new estimate. A multistage interference cancellator with i stages and K users is presented in figure 3.

In a multipath environment a RAKE receiver can be used to get the advantage of the diversity of the channel. Since the RAKE receiver requires the channel estimates a decision directed interference cancellation (DDIC) seems like an obvious choice instead a non-decision directed interference cancellation scheme. Authors , however, propose a combination of NDDIC and DDIC in order to decrease the complexity of the receiver. The proposed hybrid IC scheme works as follows. At first few stages of NDDIC is carried out. In the multipath environment each path is treated as a separate user. The energies of different paths of different users are ordered independently and cancelled one by one according to the decreasing signal power. Assumed that there are K users and the signal is received through P paths there are KP interference cancellation units (like figure 2) in the NDDIC part of the receiver (in figure 3 KP instead of K).

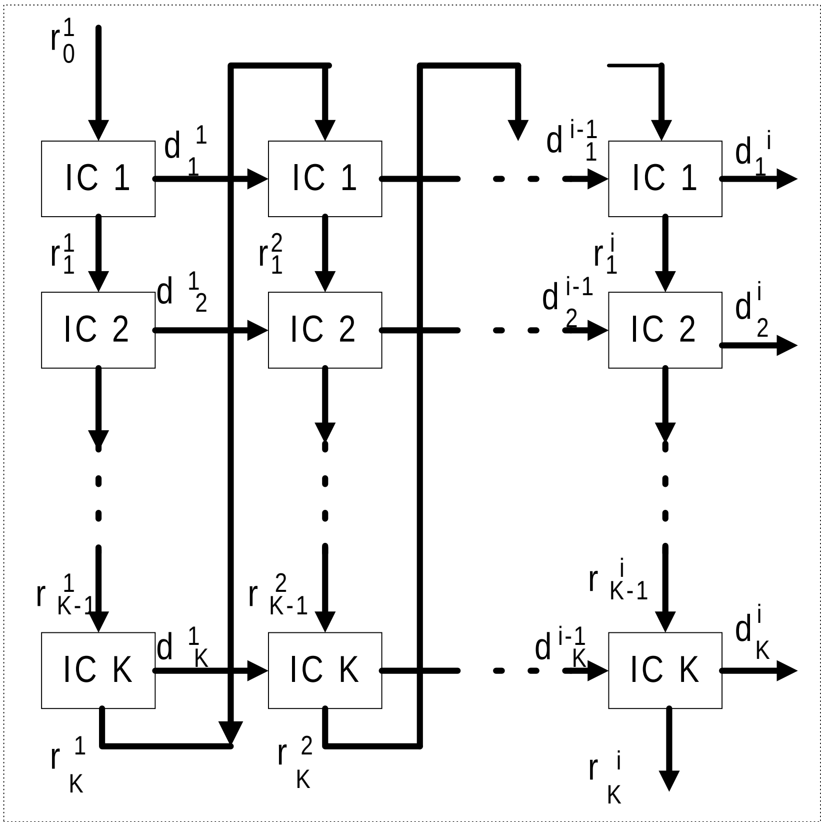

Figure 3. Multistage nondecision directed interference cancellator [12].

After few stages of NDDIC multiple access interference of each path has been reduced enough and the channel parameters can be estimated using e.g. pilot symbols. These estimates are used to rank the users according to their total received signal power. In this stage also different paths of a user are collected to the same group. In the last stage of the hybrid IC scheme a RAKE receiver is combined with DDIC to benefit both from the diversity and the removal of Gaussian noise. This stage is presented in figure 4. In the figure r'_{K-1} represents the resulting baseband signal before the DDIC unit K. $d'_{p,k}$ denotes the signal estimate of the *k*th user's *p*th path. This is one the P estimates which from KP outputs of NDDIC unit belong to the user k, see figure 5. For the DDIC scheme a similar procedure as in NDDIC is carried out. First the new estimates of the signals corresponding to the strongest user's paths are obtained. This is done successively since if the received multipath is regenerated and a conventional RAKE is used, the inter symbol interference which was partly removed in NDDIC would be introduced again. In the modified RAKE the signals are fed separately to the combiner. After the symbols have been detected the estimated channel parameters are used to regenerate the signals corresponding to the user's all paths. These signals are then cancelled from the composite baseband signal. The scheme is repeated successively for all the users. If more than one stage of RAKE and DDIC is implemented the regenerated signals corresponding to different paths are fed to the next stage in the same way as to the first stage.

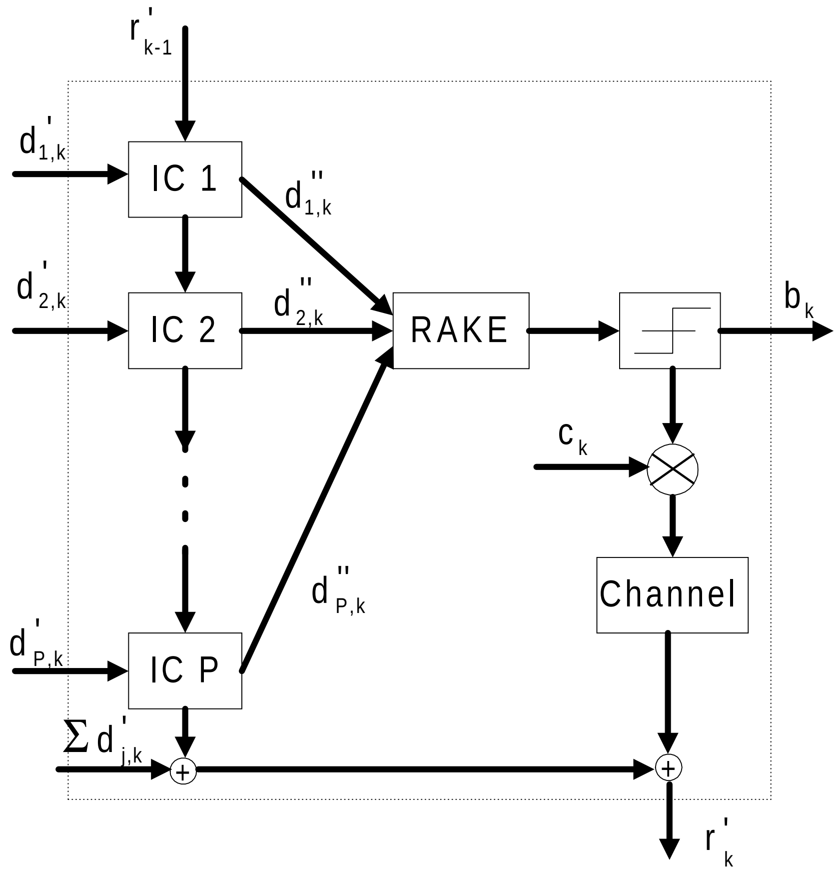

Figure 4. Decision directed interference cancellation in combination with a modified RAKE [12].

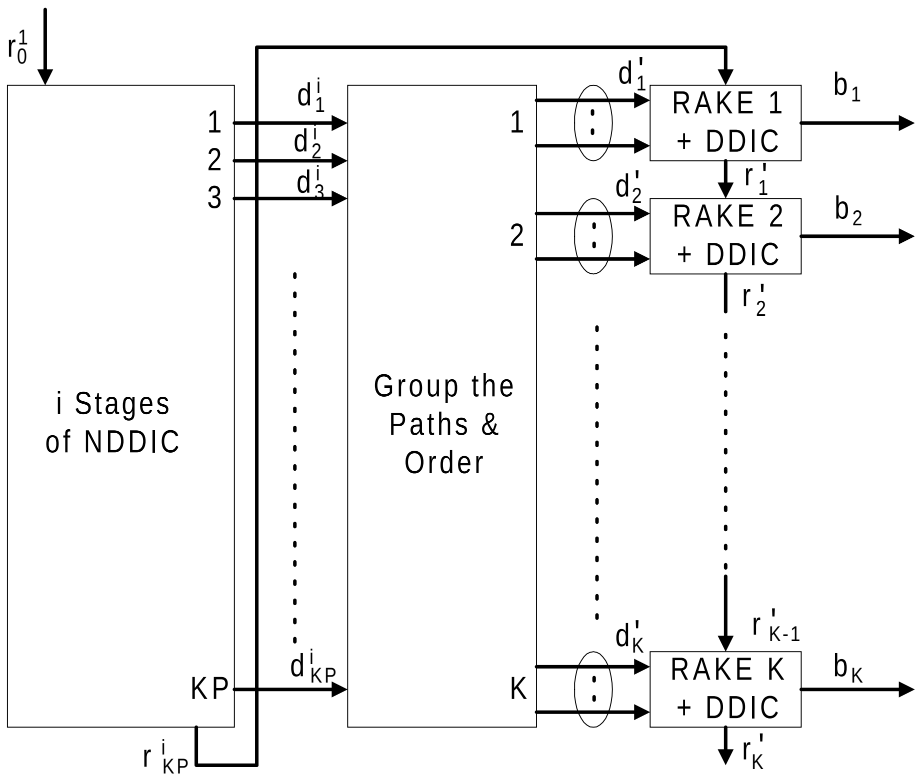

Figure 5. Hybrid interference cancellation scheme [12].

Authors simulated the presented hybrid IC scheme (4 NDDIC stages + 1 DDIC stage). They concluded that a pure NDDIC with 5 stages has worse performance than the hybrid scheme. The reason was that channel parameters were not used in the cancellation. The performance of a five stage DDIC was equivalent to the performance of a hybrid scheme in the low E_b/N_0 area where Gaussian noise was dominating. In the high E_b/N_0 area the hybrid scheme worked better. Authors explained this result so that the hybrid scheme suppressed the ISI before the channel parameters were estimated. In the DDIC scheme poor channel estimates could lead to detection errors.

The presented hybrid IC scheme was simulated in a multirate environment. Interference cancellation seemed to work well in a multi channel system. In a simulation where 10 QPSK users each transmitting over two channels the performance was close to a single BPSK user performance. Authors also concluded that for high bitrate users multi channel solution is preferred over a mixed modulation scheme. The reason was that the BER performance of 16-QAM modulation was worse than the performance of the multi channel scheme.

4. MULTIRATE RECEIVERS IN 3RD GEN. NETWORKS

At the moment standards for 3rd generation networks are being developed. One of the main requirements of the future wireless networks is that they must support different services and provide high data rates. Consequently, receivers must be able to handle multi-rate transmission. In one of the earlier seminar presentations [9] CDMA candidates for 3rd generation standards were presented. In here a short review of the ETSI SMG2 W-CDMA receiver concept is presented. In addition, some information about the development in the US standardisation is shown.

In the 3rd generation development work chip rate is usually assumed fixed and QPSK type modulation is used. Multi-rate transmission is provided with multi-codes and by changing the spreading factor. In the ETSI SMG2 W-CDMA it is possible to have different chip rates in the same network but the chip rate is assumed constant during the connection. In 3rd generation wideband CDMA solutions a normal RAKE receiver is used to get the benefit from multipath diversity. Because of the complexity of the receiver very many parallel code channels are not considered as a feasible solution in the forward link. On the other hand, in the reverse link many parallel multicodes may cause amplitude variations and are for this reason seen non-preferable. However for moderate bitrates multicode transmission is a good solution.

In the US the first phase of the high speed data enhancement for IS-95 standard has been done with multicodes both in the forward and reverse links. A very important decision criterion in the development was that the new system must be compatible with the existing IS-95 standard. Also modifications to the BTS hardware were required to be as small as possible. Keeping these requirements in mind network capacity and channel throughput performance were considered when the choice was made. Multicode solution was seen to fulfil the criteria. In addition, because the supported data rates are only up to four times the basic rate i.e. at maximum four parallel code channels can be used the receiver structure remains simple enough. Also in the reverse link, the amplitude variations are not seen too difficult a problem because of the small number of parallel channels.

In the ETSI SMG2 W-CDMA proposal the transmission is done by using one code and a variable spreading factor for moderate bitrates. In the solution, all the rate information e.g. the spreading factor is transmitted through a constant parameter control channel. For high bitrates multi-codes are used together with a variable spreading factor. The reason why multi code transmission was introduced is that high data rates cannot be supported solely by changing the spreading factor. On the other hand, a pure multi code transmission is unsuitable because high data rates are to be supported. Under the circumstances, the number of parallel channels would be very high and the receiver structure excessively complex.

5. CONCLUSIONS

Wideband CDMA systems are among the most promising candidates as the 3 generation wireless network standards. In the third generation standards multi-rate concept is one of the key feature. Consequently, receiver structures which support multi-rate transmission are a very interesting and important topic. There are many ways to provide multi-rate transmission. As an example it was mentioned multi-modulation, variable chip rate, variable spreading factor and the multi-channel schemes. In practise, multi channel and variable spreading factor solutions seem to be the most popular candidates. However, there are some problems in these solutions too. For the variable spreading factor solution it may be difficult to find orthogonal codes in the forward link. In addition, the protection against external interference is low because of the low spreading factor. For multicode transmission the receiver structure may become very complex if many parallel code channels are introduced. In addition, in the reverse link a high number of codes can be problematic from the power amplifier point of view because many parallel codes give rise to large amplitude variations for which reason a linear amplifier should be used. In this presentation we also reviewed articles of multiuser detection and interference cancelation in a multi-rate framework. These techniques are promising but are not considered as an alternative in the development of third generation systems. The reason is that at the moment these solutions are still too complex for practical solutions. Despite their complexity these techniques may become useful in the future, especially in a multirate environment. When different users have different bitrates near-far effects are likely to be worse than in conventional systems. IC /MUD can benefit from this phenomenon because the higher a user’s energy level is the more accurately channel parameters can be estimated. This facilitates accurate cancellation of the multiple access interference. Another important factor increasing the usability of IC/MUD in a multi-rate environment is that as the data rates are high the number of coexisting active users is likely to be relatively small which decreases the complexity of the receiver.

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