AN ITERATIVE MULTIUSER DETECTION RECEIVER FOR 3GPP WITH ANTENNA ARRAYS: PERFORMANCE IN TERMS OF BER, CELL SIZE AND CAPACITY

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Abstract- **This paper discusses the implementation of a very powerful but computationally efficient, iterative multi-user detector, intended for use as the basestation physical layer receiver for Wideband CDMA. This multi-user detector is unique in that it is fully compliant with the release '99 3GPP standard, a result that has not been shown before. The transmitter chain is discussed before the channel model used is introduced. The receiver design approach is then discussed. Special consideration is given to show how channel estimation is integrated into the receiver. We show single cell performance results that indicate a capacity increase of approximately three times over the "conventional" receiver implementation is possible (with and without antenna arrays). Results are then shown using a cell dimensioning simulation tool to indicate the overall gain in terms of increase in cell size. Here we can show that a gain of approximately 50% of the cell size is possible with such a multi-user detection approach. The dimensioning tool is also used to show the increase in capacity for a fixed cell size. Here we can show that a gain in the order of 330% is possible, compared to a conventional receiver approach.**

INTRODUCTON

The introduction of cellular wireless systems in the 1980s has resulted in a huge demand for personal communication services. This demand has made larger-capacity systems necessary, which has been partially satisfied by the introduction of second generation digital systems. New third generation systems are now undergoing standardization [7] and will require even more efficient utilization of the spectrum if the high bandwidth features and larger capacity are to become a reality.

The discovery of the optimum receiver [1] showed the best performance that a multi-user receiver can achieve, but with complexity that is exponential with the number of users. Suboptimum techniques [3] have been published but unfortunately most of these techniques have inherent disadvantages which make them difficult to implement, or provide very limited performance improvement in a "real world" communications environment, as seen in terrestrial mobile radio.

This paper is based on the concepts of Iterative Multiuser Detection (IMUD) [8, 2, 4]. An IMUD uses concepts from turbo codes [13] or more specifically serial concatenated turbo codes [14] where the CDMA system is viewed as the inner code and the outer code is the code associated with each user. When this system model is used a receiver structure similar to a serial concatenated turbo decoder can be determined which performs detection and decoding in an iterative or multi-stage way.

IMUD techniques have many variations and the complexity of the system depends largely on the implementation selected. In this work we utilize methods [2,11,9,5] as these methods have low computational complexity, where the total complexity increases at a linear rate with the number of users in the system. This is achieved while still being able to achieve the performance of the optimal receiver.

In this paper we remove the channel estimation assumption and utilize the entire 3GPP release '99 physical layer transmitter chain. This transmitter chain includes a fixed code selection and interleaver design. We include in our performance results all the losses due to puncturing/padding and user-specific pilot channels, as defined by the particular scenarios that we have used. The aim therefore of the paper is to illustrate the actual gains that are possible with the IMUD in an as realistic as possible 3GPP system. Normally the performance for multi-user detection is described only in terms the bit error rate (BER) of a single cell. We use our frame error rate (FER) results from the single cell environment and apply them to a cell dimensioning tool [17]. We then use this tool to determine both the increase in cell size for a fixed number of users, and the increase in users for a fixed cell size. The increase in cell size means that the IMUD can be used to reduce initial deployment costs of 3G systems by reducing the required number of basestations. The capacity increase for a fixed cell size shows that the IMUD can also be used successfully for increasing the overall number of users per cell or the average data rate per user in a cell.

SYSTEM MODEL

Transmitter Configuration

The transmitter uplink FDD design is as per the release '99 3GPP standard [6,7]. The bit source for each transport channel has a CRC attached, is block concatenated and segmented, channel coding is added, before radio frame equalization is performed. The first interleaving is performed before the radio frame segmentation and rate matching is performed. Each transport channel is then multiplexed before physical channel segmentation takes place. Following physical channel interleaving the spreading, scrambling, and modulation is performed. This is performed for each user based on a large set of parameters defining the configuration for each user.

For the results in this paper, all users have the same configuration and data rate which makes the parameter selection somewhat easier. The simulation sampling rate at the output of the transmitter is at the chip rate.

Channel Model

A baseband equivalent channel model for this work is used. The transmitter output is passed into a multipath fading model. This fading model generates *P* different delayed versions of the original signal, each path has a different average signal power and each path contains a Rayleigh fading model (Jakes), where the rate of the fading is dependent on the vehicle speed. This model is essentially a wide sense stationary with uncorrelated scatterers (WSSUS).

Each of these *P* paths is passed independently to the linear antenna array model, consisting of *E* antennas, as each path's direction of arrival (DOA) is different. Each path is multiplied by a set of phase offsets (steering vector) based on its DOA, which when multiplied with the path signal form the baseband signal at each antenna element output. The results for each path, for each antenna element, are added to form the user received signal. The addition of other users is then performed to form the total user received signal for each antenna element. Finally additive white Gaussian noise (AWGN) is added to each antenna element, based on the particular Eb/No setting. This then is the channel output, input to the receiver.

Channel Parameters

In the above section the general channel model was described. Here the specific channel model utilized to generate the results is described. For the results shown here the multipath fading model consists of three taps with three weights as described in Table 1.

Table 1 Vehicular A Channel Model

	Path 1	Path 2	Path 3
Delay (chips)	0	1	2
Average Power (dB)	0	-2	-7

This channel is an approximation to the first three taps of the ETSI Vehicular A channel [ETSITR101112] and was chosen to illustrate the system in a "typical" channel. The fading on each path is independent and Rayleigh distributed, generated using the Jakes Model.

The antenna array model (when used in the results) is based on a universal linear array (ULA), where each element of the array is spaced at ½ wavelength. The steering vector is

$$\underline{g} = [1, e^{j\pi \sin(\vartheta^{(k)})}, \bullet\bullet\bullet, e^{j(E-1)\pi \sin(\vartheta^{(k)})}]^T$$

where $\vartheta^{(k)}$ is the direction of arrival for user *k*.

In the model used here, each user is given a fixed "user DOA" and the DOA of the paths for that user are relative to this "user DOA". The valid DOA's are from 30 degrees to 150 degrees where boresight is 90 degrees (this assumes a Y shaped backplane at a basestation to remove interference from the other two sectors. The path DOA's used in this work are shown in Table 2.

Table 2 Relative Path DOAs

	Path 1	Path 2	Path 3
DOA difference from "user DOA"	-5 deg.	4 deg.	9 deg.

The user DOA is distributed evenly over the valid 120 degrees of the antenna array, depending on the number of users.

RECEIVER DESIGN

Receiver Configuration

Figure 1 shows a single unit from the iterative multi-user receiver implementation. This is 3GPP specific but follows closely the generic configuration presented in [9]. This illustrates that the received signal is demodulated, de-interleaved and decoded with a conventional CDMA receiver, with the exception that a soft-input soft-output (SISO) MAP decoder [12] is used, instead of the conventional Viterbi Decoder.

The soft outputs from the MAP decoder provide the input to the re-transmitter module, which re-performs the transmission chain which is known at the basestation. Following this, the channel re-transmitter includes all the effects from the channel, based on the channel estimation.

The output re-created signal then provides an estimate of the chip sampled (or oversampled) received signal for this particular user. The output signals from all other users are then subtracted from the original received signal (with the correct delay) to create an improved estimate of the signal appropriate to this user.

If the signal estimate from all other users was perfect then cancellation from the original received signal would leave only noise and the signal from this particular user. This would mean that this user would achieve single user performance (no-interference performance). Due to the utilization of interleaving and MAP decoding the signal estimates are relatively good and the interference cancellation improves over stages (iterations). After multiple stages (we utilize three) the improvement in performance is very large and the "no-interference" single user performance can be approached, even when the number of users (K) exceeds the processing gain (N).

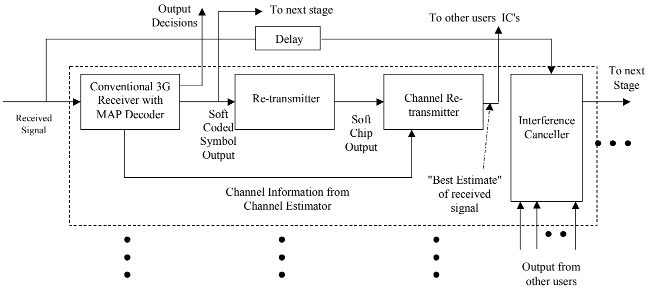

Figure 1 One Unit of the Iterative MUD

In Figure 1 we showed only one unit from the multi-user detector. In Figure 2 we show how this basic module can be concatenated to develop a receiver that can operate over multiple stages and over more than one user. It is clear from this picture also that the computational complexity of the system only grows in a linear way with the number of users. For each additional user that the base station supports another row in this figure is required.

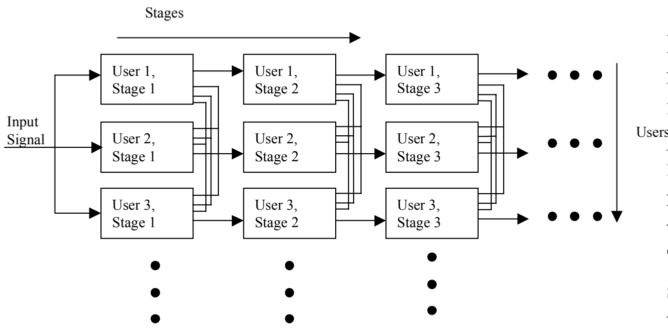

Figure 2 Iterative MUD Block Diagram

NUMERICAL RESULTS

In this section we show a number of multi-user performance results of our system with and without antenna arrays. With each performance curve we show the "optimum", or single user performance and the "conventional" receiver performance. This allows us to compare the performance of our receiver with known receiver performance.

Single Antenna Results

Here we show the results for a single antenna system. In Figure 3 we show the performance at a higher processing gain of N=16, where each user has an effective data rate of 64kbps. The system load is K=25 users. The channel conditions are the approximation to the Vehicular A channel as defined in the system model. In this result our receiver on the 3rd stage reaches a performance within 6dB of the "optimum" or single user result, while again the "conventional" receiver (1st Stage) result floors above an error rate of 10^{-1}. In this results and all following we maintain perfect average power for each user instead of implementing power control as we know that the results are similar with power control at this speed [16].

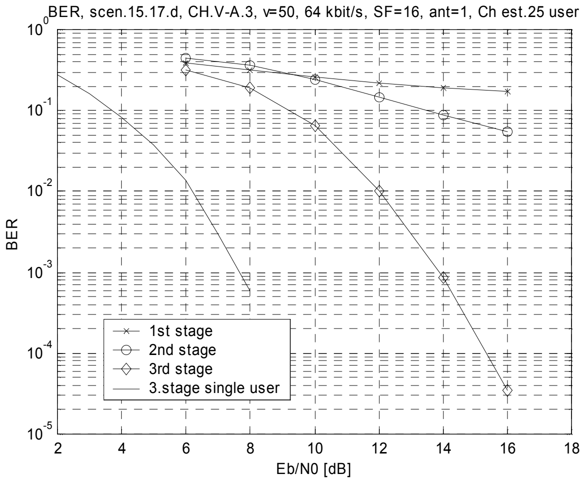

Figure 3 IMUD Performance with N=16, K=26

Antenna Array Results

Even though the cost and complexity of antenna array may be a deterrent, there is nevertheless a lot of interest in the performance of antenna arrays in 3GPP. The purpose of the result below is to show that the integration of an antenna array into this multi-user receiver concept is a natural and obvious extension of the receiver.

The result in Figure 4 shows the performance for a system with E=4 antenna elements arranged as a ULA with a 120 degree sector. Both the DOA and channel are estimated and the processing gain *N*=16, where *K*=70 users are active. Perfect average power levels are again assumed. In this case the "conventional" receiver performance has severe flooring problems, however the Iterative MUD achieves results within 3dB of the optimum performance.

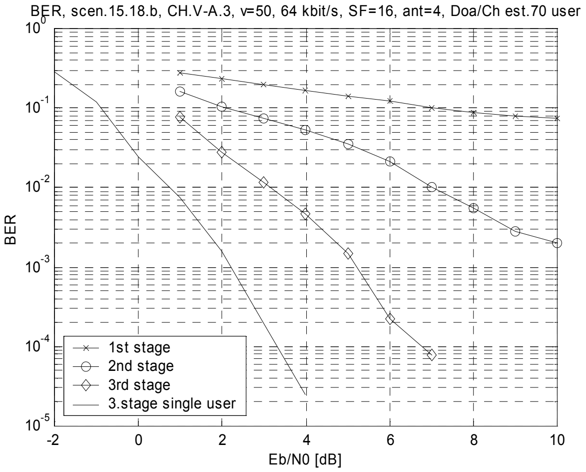

Figure 4 IMUD Performance with N=16, E=4, K=70

CELL DIMENSIONING RESULTS

In order to determine the IMUD performance in terms of capacity, coverage and QoS, system level simulations have to be applied. Ascom has developed such a simulator [17], which allows not only the evaluation and optimization of Tx-/Rx-algorithms but also of radio resource management (RRM) algorithms and the UMTS radio access network as a whole. This tool takes into account things not included in the link-level simulations described above, like mobile position, path loss, shadowing, inter-cell interference, and most importantly power control in a multi-user environment.

IMUD Capacity Gain

Figure 5 displays the gain in capacity (users per cell), which can be obtained by the use of MUD in the basestation receiver. In the simulated scenario 384 kbit/s high rate (UDD) users have been equally distributed over an area, which is partitioned into 7 cells. The outage probability is the percentage of users whose simulated mean SIR is below the required target SIR. The target SIR is determined from the Frame Error Rate (FER), which is required for the given service and can be obtained from the FER vs. Eb/No – curves simulated in the link level testbed. For network dimensioning an outage probability of 5 % is usually considered to be tolerable. At this value approximately 2.3 users per cell can be served simultaneously, if a conventional receiver is applied. The application of MUD increases this capacity up to 7.7 simultaneous users per cell. In the range of 4 users per cell the MUD is able to cancel all intracell interference, but for further increasing cell loads these users add to the intracell interference, that can not be cancelled.

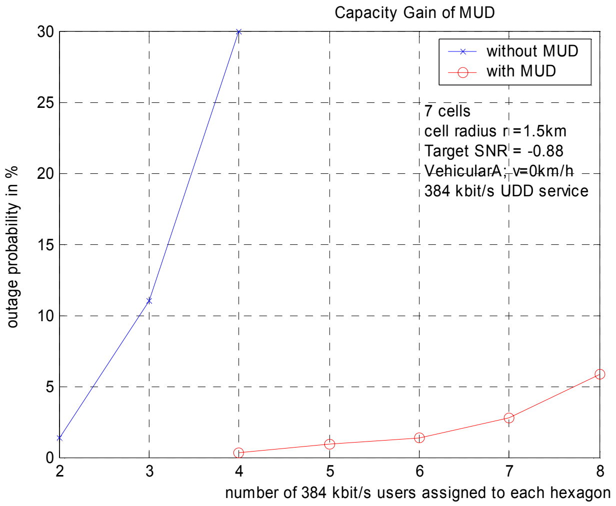

Figure 5 System Level Capacity Gains

The simulated capacity gain factor of 7.7/2.3=3.34. If the total intracell interference can be cancelled with a multi-user receiver then the ratio of the interference reduction equals

$$r = \frac{\text{intra} + \text{intercell interference}}{\text{intercell interference}} \qquad (1)$$

In macro cellular environments it can be assumed that inter cell interference is approximately half as much as intracell interference[HarAntWCDMA p.156], which yields r =3. The similarity between the simulated capacity gain and the interference reduction ratio shows that the assumption that the interference grows linearly with the number of users in the system is valid.

IMUD Coverage Gain

For network operators the capacity gain determined in the previous section is particularly valuable if the network is well established and the number of users increases. However, immediately after the rollout of the system usually only moderate numbers of users have to be served. In this state the size of the cells is not limited by the capacity but by the coverage.

Figure 6 displays that for the given scenario the cell radius of a lowly loaded cell can be increased due to the use of MUD by 0.7 km at an outage probability of 5%.

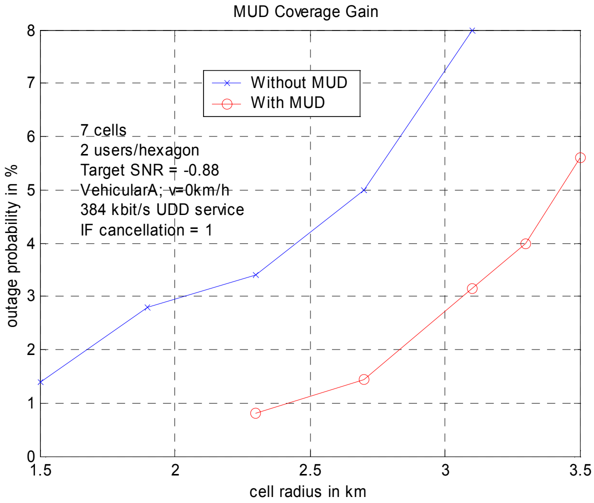

Figure 6 System Level Coverage Gains

This increase in cell size from 2.7 km to 3.4 km equates to an overall cell size increase of approximately 50%. The advantages of this is clearly a reduction in the initial number of basestations required by 33% leading to large cost savings for operators.

CONCLUSIONS

In this paper we have discussed a 3GPP Release '99 compatible Iterative Multi-user receiver. We have studied issues related to a real implementation and have reduced the typical assumptions on the receiver design by including channel estimation and tracking as part of the receiver.

We have described the transmitter chain and the channel models used to produce the performance results. These channel models include fast fading on every tap of the assumed wide sense stationary uncorrelated scattering (WSSUS) channel model. For the results with a multi-element antenna array we also estimate direction of arrival.

We have described our receiver design and discussed the implementation architecture, which is a very modular design. We illustrated that the tasks of channel and DOA estimation have been implemented. These tasks must be deeply embedded in the receiver design as the receiver assists the estimators to determine the channel and the estimators likewise assist the receiver in determining which data bits were sent. We argue that this is the only method of designing receivers for high interference environments, where careful consideration of all available information is required to achieve a successful design.

We have shown single cell bit error rate performance results for the design with and without antenna arrays, at high and low spreading factors. We have compared results with a conventional receiver and the "optimum" receiver [1] and shown that we can approach the optimum performance even when the number of users exceeds the processing gain. This paper confirms that the IMUD results presented previously in very simple scenarios can indeed be extended to the complexities of the 3GPP standard and still achieve large performance improvements.

Finally we showed the performance improvement in terms of capacity gain or cell size gain in the multi-cell environment, by using a cell dimensioning tool.. These results show that with the IMUD, cell size can be increased by at least 50% - a very important advantage during initial deployment of 3G systems. For fixed cell sizes, the increase in capacity using the IMUD is approximately 3.3 times over that with a conventional receiver. Larger gains are expected for the antenna array solution.

This paper demonstrates that a base station multi-user detector fully compatible with the 3GPP standard is feasible. The complexity of the proposed solution increases only linearly with the number of users, and a simple architecture for the detector based on re-use of simple well-understood building blocks has been presented.

The paper also shows the advantages of this approach. Merely by increasing the signal processing complexity of a 3GPP base station, we can either increase cell size by 50% or cell capacity by 330%.

ACKNOWLEGMENT

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