3GPP TSG RAN WG 1 ***TSGR1#19 R1-01-0203***
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Source: Siemens[1]

Title: Description of the eigenbeamformer concept (update) and performance evaluation

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1 Introduction

Currently in TSG RAN WG 1 the usage of more than 2 antenna elements at the Node B for closed loop transmit diversity is discussed. Here, the optimum antenna weights are calculated at the UE based on measurements on the downlink channels. These antenna weights are then fed back to the Node B.

Hereby, the bandwith of the uplink channel is a limited resource. With increasing the number of antenna elements by using an extension of the Release '99 TxD modes, the amount of necessary feedback is increased. When keeping the uplink bandwith the same the antenna weights cannot be adjusted fast enough to account for fast fading. Hence, for higher velocities of the UE the gain due to the additional antenna elements is low.

However there are ways to reduce the necessary feedback bandwith if the antenna channel paths are correlated. Recently the eigenbeamer concept has been proposed as a favourable solution. In this paper we present an update of the eigenbeamformer concept as presented in [1]. The main modifications are:

- The long term properties of the antenna channel paths are no longer evaluated for each temporal tap. When calculating the covariance matrix averaging over taps is done implicitly. Thus, only one spatial covariance matrix is used for subsequent eigenanalysis and computational effort is reduced.
- The application of STTD coding on the eigenbeams is postponed for later extensions. It can still be taken into account in later considerations.
- The previously presented simulation results in [2] are updated. One slot delay has now been used as required by the simulation assumptions.
- The short term selection now takes the energy of all the temporal taps into account and not only the dominant tap.

The presented information in this contribution can be used as input for the TR on Tx diversity solutions for multiple antennas.

2 Description of the Eigenbeamformer

The general idea behind the eigenbeamformer is a decorrelation of the antenna signal paths to achieve a reduction in dimension of the spatial space. This enables subsequent short term processing at the UE to sufficiently mitigate fast fading.

This decorrelation is performed by exploiting the long term properties of the propagation paths based on an eigenanalysis of its long term spatial covariance matrix. The eigenvectors (in the sequel also called eigenbeams) with the largest eigenvalues (largest average UE receive power) are determined and fed back step by step to the Node B. This process takes place on the same time scale as the physical UE movement. Accordingly, the required operations in the UE as well as required feedback bits are distributed over a very large number of slots.

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[1] In cooperation with the Institute for Circuit Theory and Signal Processing of Munich University of Technology, Germany

In addition, a short term selection between the eigenbeams is carried out at the UE to account for fast fading. This information is fed back to the Node B on (almost) every slot.

By this technique we are efficiently able to address a larger number of antenna elements providing large beamforming gains at higher velocities.

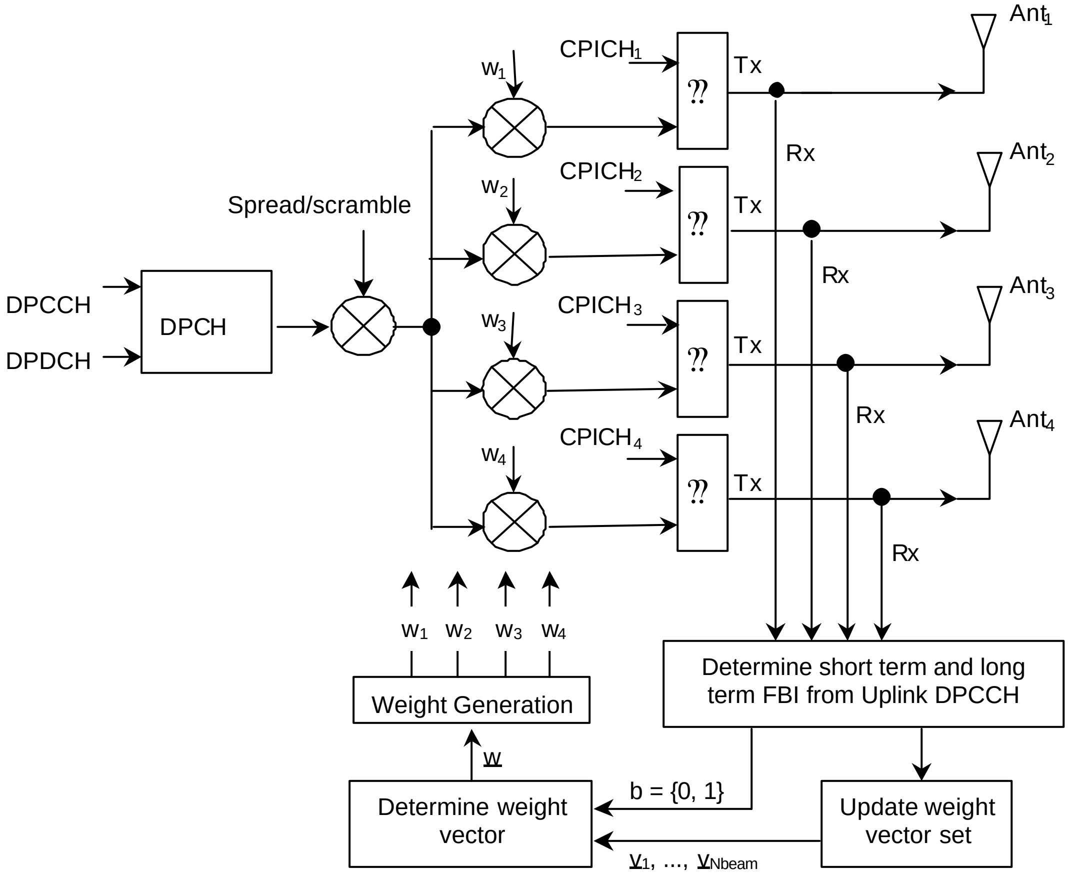

Figure 1: Generic Downlink transmitter at the Node B with M = 4 antenna elements

Figures 1 and 2 show the generic architecture of the eigenbeamformer concept at the Node B and the UE. In the following sections we focus on a system with $M = 4$ antenna elements and $N_{beam} = 2$ or 4 eigenvectors. However the eigenbeamformer is easily extendable to more antenna elements.

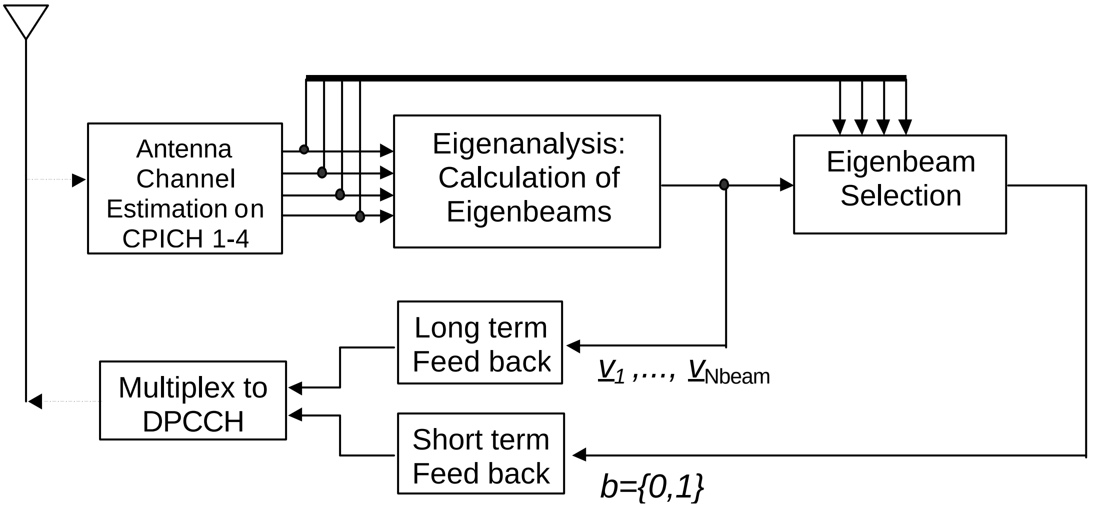

Figure 2: Generic eigenbeamformer structure at the UE for M = 4

2.1 Calculation of the Dominant Eigenvectors

Using orthogonal pilot sequences transmitted from the Node B antenna elements, the UE estimates the short term spatial covariance matrix averaged over the temporal taps of the channel.

$$\mathbf{R}_{\mathrm{ST}} = \sum_{n=1}^{N} \mathbf{h}_n \mathbf{h}_n^H \tag{1}$$

The column vector $\mathbf{h}_n = [h_{n1}, h_{n2}, \ldots, h_{nM}]^T$ denotes the channel vector of the n-th temporal tap. The number of taps is denoted by *N; M* = 4 antenna elements are assumed. The long term spatial covariance matrix is obtained by averaging the short term matrix using a forgetting factor ρ.

$$\mathbf{R}_{\mathrm{LT}}(i) = \rho \mathbf{R}_{\mathrm{LT}}(i-1) + (1-\rho)\,\mathbf{R}_{\mathrm{ST}}(i) \tag{2}$$

The symbol *i* denotes the time index. It is sufficient to perform an update once every frame or even in larger intervals.

Decorrelation in space is achieved by an eigenanalysis of the long term spatial covariance matrix according to

$$\mathbf{R}_{\mathrm{LT}}\,\mathbf{V} = \mathbf{V}\,\mathbf{T} \tag{3}$$

The eigenvectors (eigenbeams) to be found are columns of $\mathbf{V}$. Since the matrix $\mathbf{T}$ is diagonal by definition, transmission on different eigenbeams leads to uncorrelated fast fading. The diagonal entries indicate the long term UE received power of each beam.

Note that the eigenbeamformer automatically adjusts to various propagation environments (spatially correlated or uncorrelated). If the channel is spatially correlated, the channel can accurately be described by a small number of weighted eigenbeams. If, on the other hand, the channel has a spatial correlation of zero, no long term spatial channel information can be exploited and each eigenvector addresses only one antenna element.

2.2 Long Term Feedback Scheme

From the set of *M* = 4 eigenbeams in $\mathbf{V}$, N_{beam} vectors with the largest eigenvalues will be chosen to be transmitted in the long term feedback.

Each weight vector is a vector of complex numbers. The size of this vector equals the number of antenna elements (*M* = 4). Each complex vector element is quantized by a number of bits. There are different ways for quantization. For example, the absolute value and the phase can be quantized with 3 and 5 bits respectively. Hereby, the amount of bits can be reduced if the phase of the first vector element is set to zero. Thus, for the transmission of one eigenbeam $4 \cdot 3+3 \cdot 5 = 27$ bits are necessary.

This number applies for the direct feedback of the eigenbeams from the UE to the Node B. Also methods with progressive refinement could be used that transmit only the difference to the previously sent vector. This could reduce the subsequent update period and an increased quantization / resolution is possible.

More advanced long term feedback concepts could be used which require less feedback bits. One promising concept is to transmit the subspace with the technique of rotation matrices [3]. Rotation angles are obtained from the incremental update of the eigenbeams and quantized for transmission. This method would also provide advantages with respect to implementation since the rotation angles can be derived directly from the eigenanalysis.

The implementation of mechanisms to protect the long term bits from bit errors are for further study.

2.3 Short Term Feedback Scheme

A short term estimate of the UE received power is performed for each eigenbeam by calculating

$$P_m = \mathbf{v}_m^H \, \mathbf{R}_{\mathrm{ST}}^T \, \mathbf{v}_m = \sum_{n=1}^{N} \left| \mathbf{v}_m^T \mathbf{h}_n \right|^2 \tag{4}$$

where m characterizes the eigenbeam. The eigenbeam that results in the maximum value for the received power P_m is selected and signalled to the Node B.

For two (four) eigenbeams 1 (2) bit(s) is (are) transmitted to indicate the selection.

The overlaying long term processing enables us to switch between eigenbeams instead of antenna elements. An increasing number of antenna elements can be addressed without reducing the UE velocity threshold.

Note that the pilot symbols of the DPCCH may be used for eigenbeam verification similar to the closed loop modes in Release '99.

2.4 Format of Feedback Information

The feedback rate for the Eigenbeamformer is kept at the same rate as in Release '99 and is 1500 bit/s. The long term information bits (for feedback of eigenbeams) and the short term information bits (for feedback of eigenbeam selection) are multiplexed. The following frame format for the feedback information bits is proposed:

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
short term FB bits	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
long term FB bits	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 1: Multiplexing of long term / short term feedback information

In this multiplexing format the transmission of two eigenbeams would take 2×27=54 frames or 540 ms (see section 2.2). The eigenbeam selection of the previous slot is applied in the slots where no short term feedback information is received by the Node B (slot #15).

This format is confined to one radio frame. Thus, no counting over frame boundaries is necessary.

In a later extension with more than 4 antenna elements other formats could be used, e.g. using 3 long term feedback bits within one frame. This is for further study.

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
short term FB bits	1	1	1	1	0	1	1	1	1	0	1	1	1	1	0
long term FB bits	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1

Table 2: Multiplexing format of long term / short term information for more than 4 antenna elements

Since no long term channel information is available at the Node B for a user at the start of transmission, initial weight vectors may, for instance, address only one of the antenna elements, e.g.,

$$\mathbf{v}_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{v}_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \text{ for } M = 4 \text{ antenna elements.}$$

3 UE Complexity Evaluation

This evaluation is done by estimating the necessary complex multiplications. The numbers given can be regarded as the upper limit of complexity, since the actual implementation can still reduce the computational effort.

- Channel estimation

For all the proposed concepts on closed loop Tx diversity with $M = 4$ antenna elements, the UE has to perform a short term channel estimate over the antenna elements at N dominant temporal taps. To calculate for example $N = 4$ spatial channel estimation vectors $\mathbf{h}_n$ of length M from the global pilots, $N \cdot M = 16$ complex multiplications per slot are necessary regardless of the diversity concept used.

- Calculation of matrix update

We assume that the update in equation (2) is calculated every 5th frame to be used for the long term averaging. The covariance matrix $\mathbf{R}_{\mathrm{ST}}$ is symmetric, so for each tap $(M+1) \cdot M/2$ complex multiplications (and additions) are needed. Over all taps

$\frac{(M+1)M}{2} \frac{N}{5 \cdot 15}$ complex multiplications (and additions) per slot are needed. Assuming $N = 4$ taps this results in 0.53 complex multiplications per slot.

- Calculation of eigenbeams (long term processing)

The power method [4] can be used for the calculation of the eigenbeams. We assume that 4 iterations are sufficient to yield one dominant eigenbeam. Thus, the complexity approximately equals $4 \cdot M \cdot M$ multiplications for each eigenbeam.

We assume that for each eigenbeam this calculation is done every 300 ms which equals to 30 frames (each frame consists of 15 slots). So we have

$4 \cdot M \cdot M / 15 \cdot 30$ (= 0.14) complex multiplications per slot in average.

Advanced methods could be used based on subsequent updating of the eigenbeams, e.g. by subspace tracking algorithms, which significantly reduce the computational effort.

- Eigenbeam selection (short term processing)

For each eigenbeam the UE receive power has to be calculated, e.g. using equation (4). This implies about $2 \cdot M \cdot N$ (= 32) complex multiplications per slot. The eigenbeam which yields the highest power is selected. Since for the other proposals a similar processing as the short term selection has to be performed, about 32 complex multiplications would be also necessary. If progressive refinement is used, the complexity would be higher for these proposals.

Thus, the eigenbeamformer comes only at the cost of 0.53 + 0.14 = 0.67 complex multiplications per slot (matrix update and calculation of eigenbeams) which is relatively low with respect to 16 + 32 = 48 complex multiplications that are necessary in any case.

4 Simulation results

In this section an update of the link level simulation results is shown. The feedback delay of one slot has been incorporated now. Also, in contrast to previous simulations, the power fraction of each temporal taps is summed in the short term analysis (see equation 4). In previous simulations the eigenbeams were related to temporal taps and only the receive power of the tap corresponding to an eigenbeam was evaluated.

4.1 Simulation assumptions

The channel model was chosen according to [5] and the parameters are defined in [6] and [7]. For convenience the parameters are listed in the following table:

Bit Rate	12.2 kbps
Chip Rate	3.84 Mcps
Convolutional code rate	1/3
Carrier frequency	2 GHz
Power control rate	1500 Hz
PC error rate	4 %
PC Step Size	1 dB per antenna
Channel model(s) and UE velocities	1-path Rayleigh: 3, 10, 40, 120 km/h Modified ITU Ped A: 3, 10, 40 km/h Modified ITU Veh. A: 10, 40, 120 km/h
CL feedback bit error rate	short term 4 % long term 0 %
CL feedback delay	1 slot
TTI	20 ms
Downlink DPCH slot format	#10 or #11
Min. # of RAKE fingers for modified Vehicular A channel	5
Target FER/BlkER	1 %
Geometry (G)	0 dB
Common Pilot	-10 dB total
Correlation between antennas	different models apply, see [6]
Performance measure	$T_x E_b/I_{or}$
CL feedback rate	1500 Hz

Table 3. Simulation parameters for simulations.

For the correlation between antenna elements three scenarios have been defined in [6] and were used for the simulations. The number of eigenbeams was $N_{beam} = 2$ for the micro and macro cell scenarios. $N_{beam} = 4$ was chosen for the uncorrelated case.

The feedback error rate for short term bits for switching the eigenbeams was 4%. The long term feedback to transmit the eigenvectors was assumed to be error free. The eigenvectors were quantized with 5 bits for phase and 3 bits for amplitude of each vector element. Ideal antenna verification was assumed at the UE.

Note that averaging of the channel response over several slots is not beneficial for the short term calculations. When using averaging, the decisions for switching would be made based on averaged but time delayed channel estimates which leads to performance degradation.

4.2 Uncorrelated case

As can be seen in Figure 3, the extension of mode 1 proposed by Nokia [8] performs well up to the UE velocity of 40 km/h. However, the eigenbeamformer with N_{beam} = 4 can be an alternative to the extension of Release ’99 mode 1 as it only degrades by 1 dB at 3 km/h and has equal performance at 10 km/h and higher velocities. Using four eigenbeams in an uncorrelated scenario has the result that each antenna element is addressed by one eigenbeam and effectively switching between antenna elements is done.

For higher velocities the Release ’99 mode 1 with only two antennas will have better performance. This can be explained with the increased number of feedback bits for 4 antenna elements which cannot be transmitted fast enough.

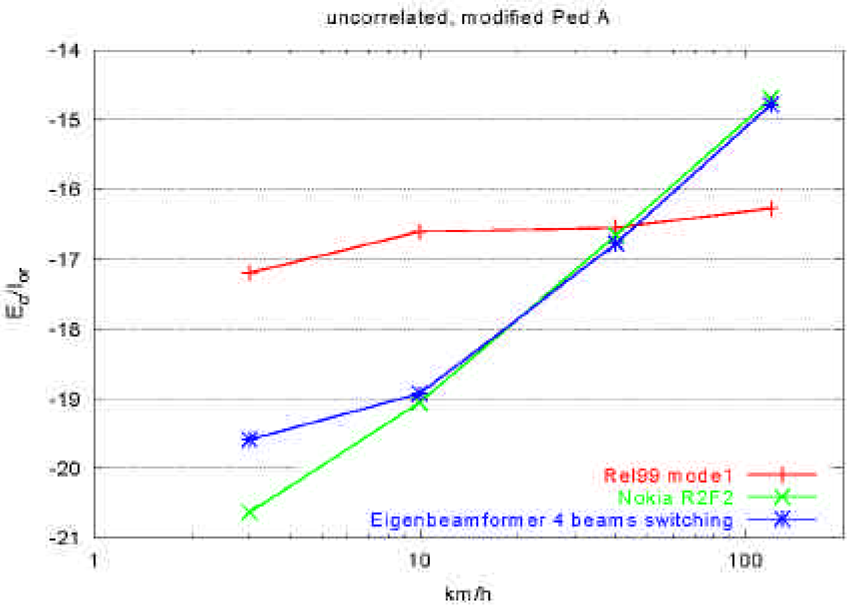

Figure 3: Simulation result for uncorrelated antenna paths

Note that the velocity of 120 km/h is shown here for explanation of the behavior and is quite unrealistic for the assumed Pedestrian A channel model.

4.3 Micro cell scenario

For the micro cell scenario N_{beam} = 2 was used. The performance of the eigenbeamformer could be improved about 1.5 dB with respect to previous results in [2]. The main reason of the improvement is the usage of the UE receive power of all taps instead of only the dominant one. As can be seen in Figure 4, for all simulated velocities the eigenbeamformer now performs best with an advantage of up to 3 dB compared to Release '99 mode 1.

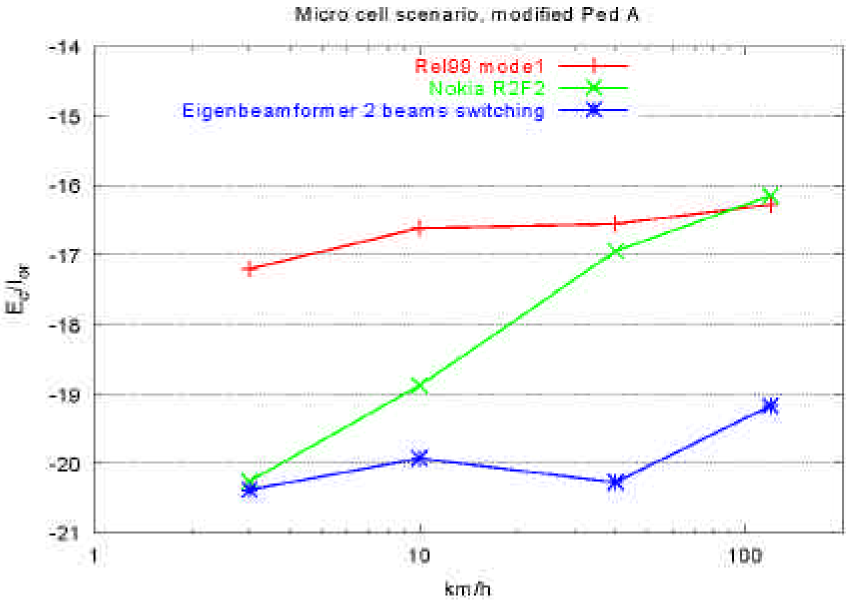

Figure 4: Simulation result for micro cell scenario

4.4 Macro cell scenario

Because of the same reason as in the micro cell scenario (using all the taps for switching) the performance of the eigenbeamformer has improved by 1.5 dB as well. So the performance difference to the extension of the mode 1 (R2F2, Nokia) was increased by the same amount. Compared to Release '99 with 2 antenna elements the eigenbeamformer will bring about 3 dB for all velocities.

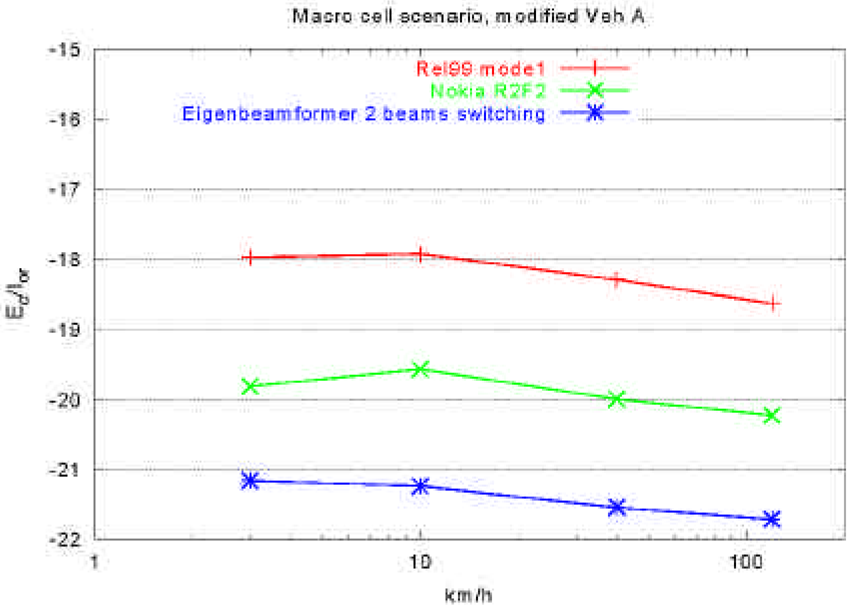

Figure 5: Simulation result for macro cell scenario

5 Conclusions

The eigenbeamformer concept has been discussed in detail with this paper. A new method on selecting the eigenbeams using all taps was presented. This leads to an improvement of about 1.5 dB compared to previous simulations.

When using correlated antennas the eigenbeamformer concept as shown here provides significant performance gain compared to R'99 mode 1 with 2 antennas. Thus, the eigenbeamformer concept is a promising candidate for the extension of closed loop transmit diversity techniques in Release 5.

The significant gain in performance is achieved mainly by being able to address additional antenna elements by long term processing and apply short term feedback only on the currently defined eigenbeams.

In the uncorrelated case the eigenbeamformer with 4 eigenbeams would still provide performance improvement compared to Release '99. This makes a one mode solution for Release 5 possible.

Further, the eigenbeamformer would be easily extendable to more antennas and it can be used regardless of the antenna configuration.

References

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[3] W. Utschick, C. Brunner, "Efficient tracking and feedback of DL-eigenbeams in WCDMA", Proc. of the 4th European Personal Mobile Communications Conference, Vienna, Feb. 2001

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[8] Nokia, "An extension of closed loop Tx diversity mode 1 for multiple Tx antennas" Tdoc R1-00-0712