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Agenda Item:

Source: Siemens[1]

Title: Advanced closed loop Tx diversity concept (eigenbeamformer)

Document for: Discussion

Summary:

Similar closed-loop Tx diversity concepts have been suggested in [1] and [2] for 4 antenna elements which exploit short-term channel fluctuations but ignore long-term spatial channel properties. Accordingly, an increase in the number of antenna elements to be addressed leads to a reduction of the UE velocity threshold for which a performance gain is achieved (except in a dominant line-of-sight scenario). This is critical since the velocity threshold is already low due to a feedback rate of 1 bit per slot.

To maximize the spectral efficiency in the downlink of WCDMA, we must be able to address more than 2, or even more than 4 antenna elements efficiently for users moving at low and higher velocities. Therefore, we present a concept which is more generic with respect to the number of antenna elements.

Our Tx transmission concept (*downlink eigenbeamformer*) is based on an eigenanalysis of the long-term spatial covariance matrices of the dominant temporal taps. The eigenbeams with the largest eigenvalues (largest average SNR) are determined and fed back step by step to the base station. This process takes place on the same time scale as the physical UE movement. Accordingly, required operations in the UE as well as required feedback bits are distributed over a very large number of slots.

In addition, a short term selection between the eigenbeams is carried out at the UE to account for fast fading if the UE is below the velocity threshold. Thus, we are efficiently able to address a large number of antenna elements by having the UE select one out of a set of, e.g., 2 eigenbeams and feed back this information to the basestation (BS) without reducing the velocity threshold.

For higher velocities – where feedback can no longer track the short-term channel variations due to fast fading – two eigenbeams, e.g., enable the application of space-time block codes on eigenbeam rather than on antenna element basis. Thus, in contrast to previous proposals, antenna and diversity gains are also available for much higher UE velocities.

Our concept can be interpreted as an extension of the Nokia concept [1] if we extend short-term processing/feedback by the possibility of simple selection in addition to phase (and weight) adjustment and include long-term processing/feedback to enable short-term processing on the basis of eigenbeams instead of antenna elements.

Finally, our concept shows lower average required operations at the UE than the Release 99 operation extended to 4 antennas while maintaining the feedback rate of 1500 bps.

[1] In cooperation with the Institute for Circuit Theory and Signal Processing of the Technische Universität München.

Table of Contents:

1. Introduction

We begin by briefly reviewing the already presented concepts for Tx diversity for 4 antenna elements proposed by Nokia [1] and Samsung [2]. Then we discuss some typical mobile radio scenarios showing inherent limitations of these proposals. This motivates the introduction of the new eigenbeamformer concept which is described in Section 2.

Nokia's proposal for 4 antenna elements is a straightforward extension of the Tx diversity mode 1 defined in release `99 [5]. The Samsung proposal, although not completely unfolded, is quite similar and, like Nokia's proposal, does not exploit long-term spatial channel properties. In both proposals, the UE is required to maximize

$$P = w^H \cdot H \cdot H^H \cdot w \qquad \text{with} \qquad H = [h_1 \; h_2 \ldots], \tag{1}$$

where h_n is the vector of spatial channel estimate of the *n*-th temporal tap and *w* denotes the (short-term) antenna weight/beamforming vector. Note that averaging over temporal taps takes place which disables efficient exploitation of the spatio-temporal channel structure.

The previous concepts do not exploit the long-term spatial channel properties and, accordingly, are optimal only for zero correlation between antenna elements in frequency non-selective channels. Examples for long-term channel properties in space and time are spatial correlation between antenna elements and dominant (temporal) taps, respectively.

Long-term fluctuations are due to different positions of the mobile. Thus, updating periods of approximately 0.5s – 1s for this long-term information are completely sufficient.

The degree of spatial correlation (uncorrelated, partially correlated, coherent) depends on the multipath geometry as well as on the antenna configuration. Note that a channel with zero spatial correlation is very unlikely if the antenna configuration is characterized by an antenna array with closely spaced (separated by approx. ½ of the carrier wavelength) antenna elements. A large spacing, on the other hand, will not be acceptable for the operators due to the negative public reaction. Note, moreover, that a 3x120° sectorisation does not make sense in spatially uncorrelated scenarios.

Let us look at three channel classes and discuss the performance of the suggested schemes in these classes.

- Class 1: Spatially uncorrelated channels (which may be frequency selective or non-selective)

  In channels with zero spatial correlation, closed-loop transmit diversity schemes are limited by the coherence time of the channel, i.e., by the velocity of the UE (and by the limited feedback bandwidth). Hence, there is a tradeoff between velocity and the ability to address a larger number of antenna elements. If the coherence time is too short, only open loop transmit diversity schemes which do not provide antenna gain/interference suppression are applicable.

- Class 2: Spatially coherent channels which are frequency non-selective

  This channel class is typically obtained if the line-of-sight (LOS) wavefront is dominant. The coherence time of the channel is of no importance to the closed-loop transmit diversity schemes [1], [2] since the weight vector changes only in the long term and, therefore, can easily be fed back. (The case where a high-speed train is racing past right next to a BS is not considered here.) If more than 4 antenna elements should be addressed, the quantization/resolution of the weight vector provided by [1] may be too low.

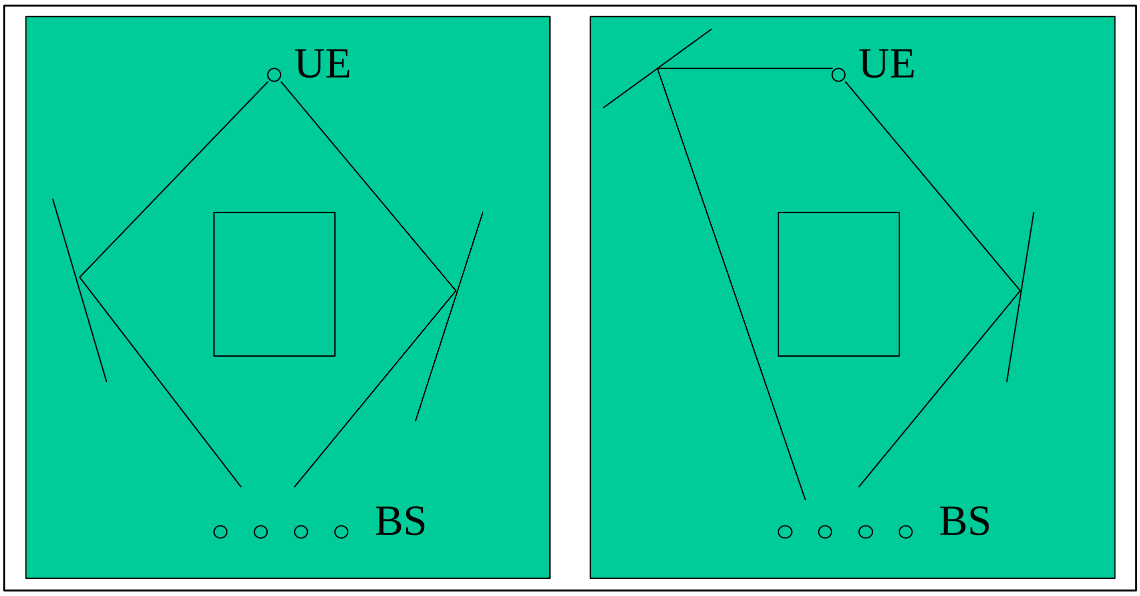


Figure 1: The left plot shows a scenario which is spatially partially correlated and frequency non-selective since the (macro) path delays are approximately equal. The scenario in the right plot is spatially coherent (for each dominant temporal tap). Since the delays can be resolved, the channel is frequency selective. Here, each (macro) path is assumed to be subject to Rayleigh fading.

- Class 3: Spatially coherent channels which are frequency selective or spatially partially correlated channels which are frequency selective or non-selective – the most relevant/important scenarios!

  A typical example for this channel class is given by a two path model where the two (macro) paths are separated in angle and may or may not be separated in chip delay, cf. Figure 1. Moreover, both (macro) paths are subject to Rayleigh fading and their mean power is approximately equal.

  Since long-term channel properties of class 3 are not exploited by the currently proposed closed-loop transmit diversity schemes, only pedestrians can be taken into account assuming 4 antenna elements. UEs suffer a significant degradation if they exceed the velocity threshold imposed by the coherence time, the feedback bandwidth, and the proposed schemes (the velocity threshold is the same as for the class 1 channel)! Moreover, the performance of the proposed schemes degrades in frequency selective channels since spatial channel estimates associated to different dominant temporal taps are averaged!

  Even though the pedestrians may form a large group, a concept which applies to users moving at larger speeds and simultaneously enables the use of more antenna elements to increase diversity and antenna gain seems to be of significant interest.

The next sections are structured as follows: Section 2 introduces the eigenbeamformer concept. Possible feedback formats (using 1 bit per slot) which differently distribute short-term and long-term feedback are presented in Section 3. Computational complexity for the UE is estimated in Section 4. Section 5 describes simulation parameters and simulation results. Finally, Section 6 draws the conclusions.

2. Description of the Downlink Eigenbeamformer

At first, long-term processing at the mobile is explained. Long-term processing comprises the estimation and the eigenanalysis of the long-term spatial covariance matrices of the dominant temporal taps. A space-time rake searcher picks the dominant eigenvectors which are fed back and used for downlink beamforming. Depending on the velocity of the UE, feedback is reduced to long-term channel properties in Section 2.2, or may also include short-term channel information, cf. Section 2.3.

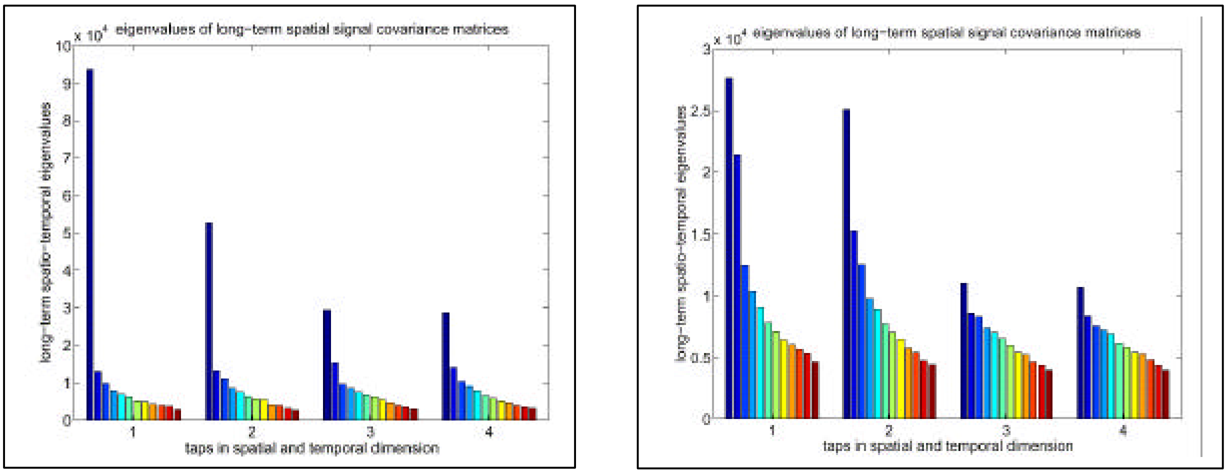


Figure 2: The long-term eigenvalues of the first four temporal taps of a channel subject to large spatial correlation (rural environment) are plotted in the left figure. In the right figure, the long-term eigenvalues are shown for a channel characterized by low spatial correlation (pico environment). The spatial eigenvalues (12 for 12 antenna elements) of each of the selected temporal taps are placed next to each other. These figures are based on a ray-tracing approach where the placing of the scattering points (and the UE) obey statistics which depend on the mobile radio environment [7].

2.1. Calculation of the Dominant Eigenvectors

With the orthogonal pilot sequences transmitted from each BS antenna element, we are able to estimate the long-term spatial covariance matrices of the dominant temporal taps in the UE. Since the second order statistics of the signals (the long-term channel properties) change slowly over time, a forgetting factor r is used which, in the example below, is applied to the long-term spatial signal covariance matrix of the n-th dominant temporal tap

$$R_n(i) = rR_n(i-1) + (1-r)h_n(i)h_n^H(i), \tag{2}$$

where i denotes the slot number. Note that it is sufficient to perform this updating once every frame or even in larger intervals but not necessarily once per slot.

The general idea behind the eigenbeamformer is a decorrelation of diversity branches (=beamforming vectors) to achieve a reduction in dimension for subsequent short-term processing and an improved short-term channel estimate at the mobile enabled by an increase in diversity and antenna gain/interference suppression.

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

$$R_n W_n = W_n \Theta_n \tag{3}$$

for each dominant temporal tap. The eigenvectors(eigenbeams) to be found are columns of W_n. Since the matrix Θ is diagonal by definition, transmission on different eigenbeams leads to uncorrelated fast fading. The diagonal entries indicate the long-term SNR of each beam.

For simplicity, let us assume that oversampling in time does not take place. Since uncorrelated scattering in space and time is assumed, temporal taps and, accordingly, eigenbeams belonging to different temporal taps are already approximately uncorrelated.

In Fig.2, the long-term spatial eigenvalues of 4 temporal taps are plotted for a scenario with a high spatial correlation on the left and a different scenario with a low spatial correlation on the right. If we limit the number of eigenbeams to 4, the 4 largest eigenvalues belong to the first 2 temporal taps in case of low spatial correlation. In case of high spatial correlation, the 4 largest eigenvalues belong to 4 different temporal taps. The corresponding eigenvectors are determined with a spatio-temporal rake searcher.

Notice that the eigenbeamformer automatically adjusts to various propagation environments (spatially correlated or uncorrelated, frequency selective or non-selective). 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. Closed Loop Long-Term Feedback Scheme

If the UE is moving at large velocities, short-term feedback is useless since the coherence time of the channel is too short. (Note that the base station is able to estimate the speed of the mobile by evaluating the uplink channel.) Therefore, the mobile must be served by two (or more) dominant eigenbeams to generate a gain in diversity. If we assume that the dominant eigenbeams have an approximately equal SNR, they can be transmitted with equal power. Accordingly, long-term feedback communicates the dominant eigenbeams determined at the UE which are required at the BS for downlink beamforming. Since they remain constant in the long term, a low feedback rate is sufficient.

(Note that there are two reasons why long-term open-loop channel estimates are not extracted in the uplink and converted to take into account the frequency gap between up- and downlink. First, the channel will not be reciprocal for up and downlink and, second, if based on closed-loop feedback, calibration is not required.)

If multipaths corresponding to eigenbeams are sufficiently separated in delay, the rake receiver at the UE is able to separate two eigenbeams and perform maximum ratio combining (MRC). If, however, the multipaths corresponding to the selected eigenbeams have equal delay, separation in time is not possible. Then separation may take place either by

- space-time block codes or by
- orthogonal channelization codes,

i.e., by applying open-loop transmission concepts to eigenbeams instead of antenna elements!

(Note that the short-term estimation of the dedicated channel is determined at the UE by applying the eigenbeams to the short-term spatio-temporal channel estimate based on the orthogonal pilots.)

Since no long-term channel information is available at the BS for a user at the initialisation, initial weight vectors may, for instance, address only one antenna element, i.e.,

$$w_1 = [1,0,0,...0], w_2 = [0,1,0,...,0],$$

etc. hold. Updating of the weight vectors takes place as the UE calculates the eigenbeams. Feedback formats are discussed in Section 3.

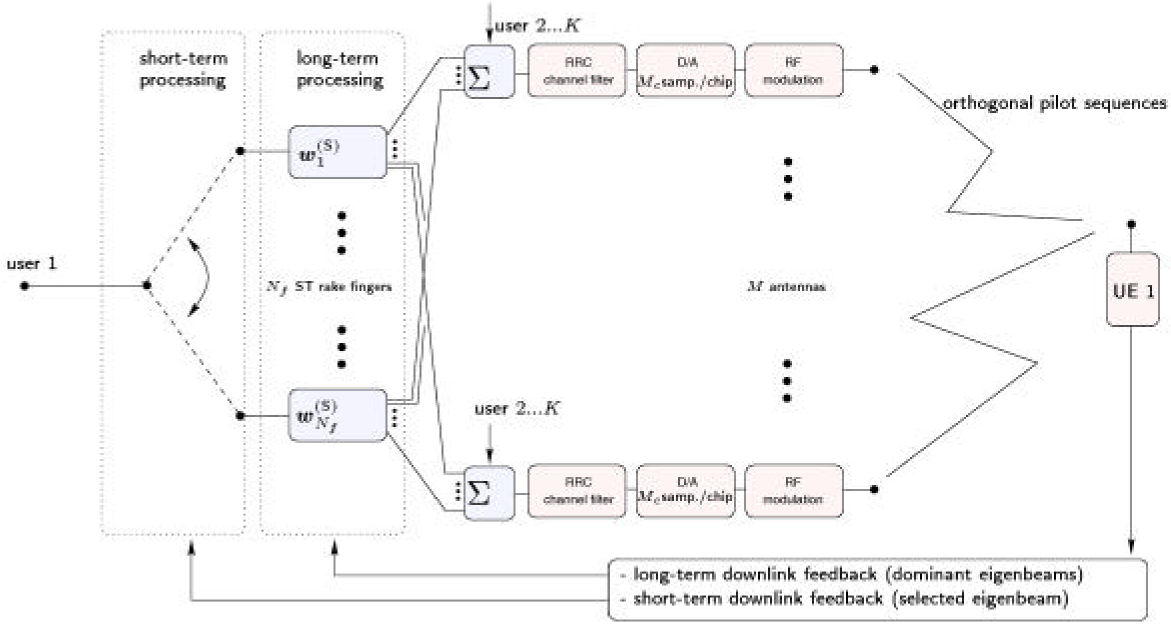


Figure 3: Structure of the downlink eigenbeamformer

2.3. Closed Loop Short-Term and Long-Term Feedback Scheme

In cases where the UEs are moving at low velocities, we propose a combined short-term and long-term feedback scheme.

A short-term term channel estimate is performed for each eigenbeam by calculating $w_m^H h_n$, where m characterizes the eigenbeam and n denotes the corresponding temporal tap of the short-term spatial channel estimate.

For short-term feedback, information can be reduced to the

- strongest eigenbeam or to the
- quantized phase shift between eigenbeams (cf. mode 1 of previous Tx scheme [5] in case of two dominant eigenbeams or [1] in case of four dominant eigenbeams).

This solution can be interpreted as an extension of the Nokia proposal [1]. An additional mode for short-term processing is introduced, namely simply selecting the strongest eigenbeam. Furthermore, long-term processing is included enabling switching/phase adjusting eigenbeams instead of antenna elements.

(Note that the short-term dedicated channel can be estimated by applying the previously selected eigenbeam to the short-term spatio-temporal channel estimate. Dedicated channel pilots may be required for antenna/eigenbeam verification.)

The structure of the downlink eigenbeamformer with combined short-term and long-term feedback is depicted in Fig.3.

For slowly moving UEs with class 3 channels, cf. Fig.1, the UE velocity threshold is not limited by the number of antenna elements to be addressed as in [1] but by the number of eigenbeams. Since, in general, two eigenbeams are sufficient, an increasing number of antenna elements can be addressed without reducing the UE velocity threshold. Furthermore, if the velocity threshold is exceeded, we simply switch to the long-term feedback scheme described in Section 2.2 without suffering a significant loss in performance. Notice, moreover, that the eigenbeamformer does not degrade in frequency selective scenarios since averaging spatial channel estimates over temporal taps does not take place.

3. Format of Feedback Information

The feedback rate for the downlink Eigenbeamformer is 1500 bps and, thus, confirms to the uplink frame format defined in release´99. The required long term information bits (for feedback of eigenbeams) and the required short term information bits (for feedback of eigenbeam selection) are multiplexed. The following frame formats for the feedback information bits are proposed:

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

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 1-2: Multiplexing format 2 of long-term/short-term feedback information.

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 1-3: Multiplexing format 3 of long-term/short-term feedback information.

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

In the first two formats, the eigenbeam selection of the previous slot is applied in the slots where no short term feedback information is received by the BS.

All formats are confined to one radio frame. Thus, no counting over frame boundaries is necessary.

In the first two formats, two modes of operation for short-term eigenbeam selection are possible:

- Mode A: Two eigenbeams are currently known at the BS. Thus, $\log_2(2) = 1$ bit is sufficient for this selection. Hence, one feedback information word has a length of one slot.

- Mode B: Four eigenbeams are currently known at the BS. Thus, $\log_2(4) = 2$ bits are needed for this selection. Hence, one feedback information word has a length of two slots.

Each eigenbeam is a vector of complex numbers. The size of this vector equals the number of antenna elements (M). Real and imaginary part of each vector element are quantized with N_{quant} bits. Thus, for the transmission of one eigenbeam $N = M*2*N_{quant}$ bits are required. For example, setting $M = 4$, $N_{quant} = 4$ yields $N = 4*2*4 = 32$ bits. Hence, the first feedback of two eigenbeams needs 64 long term feedback bits. In multiplexing format 1, this takes 64 frames or 640 ms. Consequently, in multiplexing format 2 and 3, the required period comprises 21.33 frames and 4.27 frames, respectively.

These numbers apply for the initial eigenbeams fed back from UE to BS. Later on, only an update of the eigenbeams is required. This reduces the subsequent update period significantly and an increased quantization/resolution is possible.

The signalling of the long term feedback information given here is a very basic one. Of course it would be possible to use more advanced concepts, similar to the ones suggested for the feedback for the antenna settings in conventional feedback modes.

4. UE Complexity Estimation

For all of these closed loop TX diversity proposals, the UE performs a short-term channel estimate over M antenna elements at N_{tap} dominant temporal taps. This yields N_{tap} spatial channel estimation vectors of length M.

The subsequent UE tasks for the eigenbeamformer is split into long-term (accumulation of covariance matrices + calculation of dominant eigenbeams) and short-term processing (in the following, we only discuss the short-term processing mode characterized by selection).

- Accumulation of long-term spatial covariance matrices (long-term processing)

  We assume that the short-term spatial covariance matrix is estimated once per frame and added to the long-term covariance matrix. This is done for all dominant temporal taps. For N_{tap}= 4 and M = 4, we get $N_{tap}*M*M$ = 4*4*4 = 64 complex multiplications, two real multiplications (forgetting factor), and $N_{tap}*M*M$ = 4*4*4 = 64 complex additions every frame, i.e., 4.3 complex multiplications and 4.3 complex additions per slot.

- Calculation of eigenbeams (long-term processing)

  For the first calculation of eigenbeams the power method can be used [3]. We assume that 4 iterations are sufficient to yield the dominant eigenbeam. Thus, the complexity approximately equals 4*$M*M$ multiplications. Assuming N_{beam} = 4 eigenbeams to be calculated for M = 4 antenna elements yields: $N_{beam}*4*M*M$ = 4*4*4*4 = 256 complex multiplications. Referring to the previous section, these 4 eigenbeams are described by $N_{beam}*M*2*N_{quant}$ = 4*4*2*4 = 128 bits. If we assume that the (initial) eigenanalysis should not take longer than the retransmission time, this eigenanalysis has to be performed within 128 frames in feedback format 1. Accordingly, in feedback format 2, it has to be performed within 42 frames. Hence, the average number of complex multiplications per slot is 0.13 (feedback format 1) or 0.4 (feedback format 2). For subsequent updating of the eigenbeams, subspace tracking algorithms can be applied, which significantly reduce the computational effort, cf., for instance, [4].

- Eigenbeam selection (short-term processing)

  Assuming that N_{beam} eigenbeams have already been determined by long-term processing, short-term processing is carried out in the following manner: for all N_{beam} eigenbeams (each eigenbeam is associated with a temporal tap) the inner product with the spatial channel estimation vector of the corresponding temporal tap is calculated. The eigenbeam is selected which yields the highest inner product (= the highest SNR). For N_{beam} = 4 and M = 4, we get 16 complex multiplications, 12 complex additions, and 3 comparisons. Hence, required short-term processing power is lower than in release´99 closed loop TX diversity mode 2 where (16+8+4+2)/4 = 8 inner products have to be calculated.

In total, we get the following number of complex multiplications per slot for the eigenbeamformer combining short-term and long-term processing/feedback:

4.3 (accumulation of long-term spatial covariance matrices) + 0.133 (0.4) (calculation of eigenbeams) + 16 (eigenbeam selection) = 20.43 (20.7).

This compares quite favourable with release `99 TX diversity mode 2 expanded to $M = 4$ antennas, where $8*M = 32$ complex multiplications per slot are required.

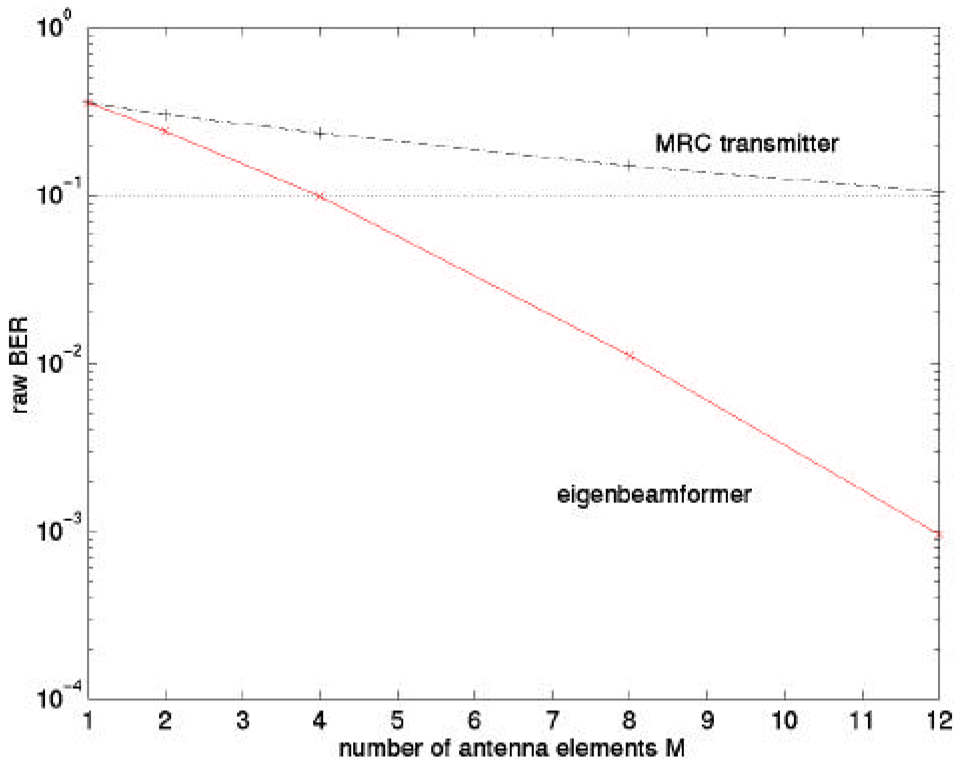
5. Simulation Results

In this section we show preliminary simulation results comparing the downlink eigenbeamformer with a maximum ratio (MRC) transmitter. The MRC transmitter is an idealised version of the Nokia concept [1] in the sense that perfect (unquantized and error free) short term feedback without filtering is assumed. Equivalently, the eigenbeams are perfectly known and feedback of eigenbeam selection is error free for the downlink eigenbeamformer.

In order to show how long-term spatial correlation can be exploited we have modified the simulation parameters described in [6] in the following manner:

- A multipath scenario consisting of two macro-paths (class 3 channel, spatially partially selective, frequency non-selective) is assumed:
  - Angles of departure: +45° and –45°
  - Equal path delays
  - Rayleigh fading per path
  - Uniform linear array, spacing of antenna elements: ½ of the carrier wavelength
- V = 40 km/h
- Ideal power control
- Geometry: 0 dB
- Performance measure: rawBER

Realistic short-term channel estimation is applied considering the pilot symbols
of only the current slot.
Realistic short term channel estimate is applied considering the pilot symbols of the current slot only. We have carried out this simulation for different numbers of antenna elements. Observe that the relative gain of the eigenbeamformer increases for more antenna elements. Due to an increasing antenna gain, the selection of eigenbeams at the mobile (and the short-term channel estimate for subsequent detection based on the selected eigenbeam) is increasingly accurate. On the other hand, the short-term spatial channel estimate taken by the MRC transmitter and fed back to the base station is NOT accurate enough to significantly exploit an increasing number of antenna elements.



6. Conclusions

We have introduced a novel downlink processing concept, namely the *downlink eigenbeamformer*. This concept can be seen as an extension to the closed-loop Tx diversity proposed in [1].

A significant gain in performance is achieved by several advantages:

- Improved antenna gain by higher quantization/resolution of the beamforming vectors (eigenbeams)!
- No averaging of short-term spatial channel estimates between temporal taps!
- Being able to add additional antenna elements without increasing short-term feedback or decreasing the UE velocity threshold. (= generic with respect to the number of antenna elements.)
- Support of high-velocity UEs by applying open-loop concepts (e.g. space-time block codes) to eigenbeams instead of antenna elements.

Moreover, the scheme works for any antenna configuration and in any multipath geometry.

To emphasize the benefits of this concept, the channel parameter set has been modified to introduce spatial correlation between antenna elements.

We suggest to further study this concept in the framework of the radio link performance enhancement study item or the corresponding work item respectively.

References

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