Antenna Weight Verification for Closed-Loop Downlink Eigenbeamforming

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***Abstract* – Adaptive antennas at the base stationsh ave a big potential to increase downlink capacity and coverage in WCDMA systems. One of the most promising techniques of adaptive antenna control is closed-loop transmit diversity. This method achieves beamforming gain as well as diversity gain by feedback of downlink fast fading characteristics from mobile station to base station. Due to the limited feedback rate, typically the best antenna weight vector chosen from a restricted set is reported. If this feedback is subject to transmission errors, two performance degrading effectso ccur: a suboptimal weight vector is used and channel estimation errors take place at the mobile station.T he latter effect arises because the mobile station derives the channel estimate for the dedicated channel from the reported weight vector and the channel estimate per antenna based on the common pilot channel. In effect, feedback errors severely distort this estimate and lead to an error floor effect. However, channel estimation can also be based on the pilot symbolsi n the dedicated channel itself. This estimate has high variance, but is not distorted by feedback errors. If both estimates are combined in a process called antenna weight verification, performance can be dramatically increased. Within this paper an antenna weight verification scheme for eigenbeamformer [1] is presented, which maximizes the estimation accuracy and eliminates the error floor. This is demonstrated by theoretical analysis and link-level simulations. It is shown that this antennaw eight verification reduces the performance degradation to 0.2 dB at 1% frame error rate.**

I. INTRODUCTION

The use of antenna arrays at the base stations of a WCDMA system hasa very big potential for increasing the capacity and coverage of downlink communication. Their main benefit isi n providing transmit diversity gain if fading on antenna elements is not identical, and beamforming gain if some information about the channel is available at the transmitter. Among several transmitter structures proposed so far are open-loop transmit diversity (space-time codes) [5] capturing only diversity gain, beamforming based on uplink measurement [7] aiming only at antennag ain, and closed-loop transmit diversity [4] achieving both. Although closed-loop transmit diversity has the potential to achieve best results, its performance is limited by the capacity of the feedback channel. In WCDMA uplink, only one bit per slot, i.e. 1500 bps, is allocated for this purpose. In order to transmit the channel information with as high precision as possible while maintaining very shortf eedback delay, it is desired to remove as much redundancy as possible from the transmitted measurement stream. One of the closed-loop downlink schemes employing this principle is the eigenbeamformer [1], which removes the redundancy present in spatial correlation of the radio channel. As hasb een shown in [2], eigenbeamformer achieves a very good performance at a wide range of mobile station speeds.

One of the problemsi ntroduced by using antenna arrays for downlink communication is more complicated dedicated channel estimation based on Common PilotC hannel(CPICH). In case of a system which uses beamforming with wide range of possible weight vectors (as opposed to beam switching and space-time codes), received power and phase of the dedicated channel depend not only on the fading situation oft he channel, but also on the antenna weightv ector used. Therefore, itb ecomes critical fort he mobile station to know precisely the weight vectoru sed by the base station. In closed-loop transmit diversity such synchronization mechanism is already in place, since mobile station explicitly requests certain weight vector via the feedback channel. As long as there are no feedback errors, the mobile station can safely assume that base station uses the selected vector. However, each time an erroro ccurs, such assumption is no longer valid, and use of the selected vector leads to considerable estimation error.

The mobile station can attempt to detect feedback errors in a process of antenna weight verification [6], which designa nd evaluation for eigenbeamformer are in the scope of thisp aper. The idea behind it is to perform a maximum a posteriori probability (MAP) hypothesis testing task based on an additional measurement. In this case, such measurement is the dedicated channel estimate obtained from pilot symbols in the Dedicated Physical Control Channel (DPCCH). It can be obtained without knowledge about antenna weight vector, but it carries much less power than CPICH and therefore is corrupted with large Gaussian error. As a result, two independent estimates of low reliability are combined to yield one high reliability estimate.

This paper is structured as follows. The transmitter, receiver and channel models for downlink eigenbeamforming are introduced in Section 2. Section 3 presents the problem of dedicated channel estimation and derives the antenna weight verification condition. The performance of MAP hypothesis testing is evaluated by theoretical analysis in Section 4. Finally, Section 5 presents the link-level simulation results for eigenbeamformer and Section 6 draws the final conclusions.

II.D OWNLINK EIGENBEAMFORMING

A.D ownlink transmission and reception model

In the downlink of a WCDMA system all channels are transmitted at the same time and the same frequency, but with different spreading codes. With multiplea ntennas availablea t

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the base station, each channel can additionally have a distinct weightv ector. Distinguished between them is the Common Pilot Channel (CPICH), which consists of orthogonal sequences transmitted from each of N_{ant} antennas with considerable fraction of base station power. The overall baseband signal (with scrambling neglected) can be expressed as

$$\mathbf{x}(c)=\sum_{\ell=1}^{N_{user}}\sqrt{P_D^{(\ell)}}\cdot\mathbf{w}_D^{(\ell)*}\cdot\left(z_D^{(\ell)}(c)*s_D^{(\ell)}(i)\right)+\sum_{m=1}^{N_{ant}}\sqrt{P_C}\cdot\mathbf{e}_m\cdot z_C^{(m)}(c). \quad (1)$$

The argument c isu sed for chip-rate signalsa nd i for symbol-rate signals. The transmit power, weight vector, spreading sequence and complex symbols for ℓ-th dedicated channel are denoted by $P_D^{(\ell)}$, $\mathbf{w}_D^{(\ell)*}$, $z_D^{(\ell)}(c)$, and $s_D^{(\ell)}(i)$ respectively, and the spreading sequence and transmit power for CPICH on m-th antenna by $z_C^{(m)}(c)$ and P_c. Furthermore, $\mathbf{e}_m$ denotes a column vector with 1 in m-th position and 0 in remaining positions, and $*$ denotes a convolution. Normalizations $\left\|\mathbf{w}_D^{(\ell)*}\right\|=1$, $\left|z_D^{(\ell)}(c)\right|=1$, and $\left|z_C^{(m)}(c)\right|=1$ hold.

Each mobile station (equipped with one receive antenna) receives a sum of contributions from each transmit antenna together with noise and interference (only one temporal tap assumed)

$$y(c)=\mathbf{h}^T\mathbf{x}(c)+n(c), \quad (2)$$

where $\mathbf{h}^T$ denotes the row vector of channel coefficients, and $n(c)\sim\mathcal{N}_C(0,\sigma^2)$ is a white complex Gaussian noise component with zero mean and variance σ^2. From (2) the dedicated channel can be isolated by performing the despreading operation:

$$\begin{aligned}y_D^{(\ell)}(i)&=\tfrac{1}{SF_D^{(\ell)}}\sum_{c=1}^{SF_D^{(\ell)}}y\left(c+i\cdot SF_D^{(\ell)}\right)z_D^{(\ell)*}(c)\\&=\sqrt{P_D^{(\ell)}}\mathbf{w}_D^{(\ell)H}\mathbf{h}\cdot s_D^{(\ell)}(i)+n_D^{(\ell)}(i)\end{aligned}, \quad (3)$$

where each symbol is corrupted by the $n_D^{(\ell)}(i)\sim\mathcal{N}_C\left(0,\sigma^2\cdot SF_D^{(\ell)-1}\right)$.

B. CPICH channel estimation

The antenna-specific orthogonal sequences within the CPICH make it possible to estimate the vector ofc hannel coefficients $\mathbf{h}$ by correlation:

$$\begin{aligned}\hat{h}^{(m)}&=\sqrt{P_C^{-1}}\tfrac{1}{SF_C}\sum_{c=1}^{SF_C}y(c)z_C^{(m)*}(c)\\&=h^{(m)}+n_C^{(m)}\end{aligned} \quad (4)$$

The resulting estimate is corrupted by a zero-mean complex Gaussian component $n_C^{(m)}\sim\mathcal{N}_C\left(0,\sigma^2\cdot SF_C^{-1}P_C^{-1}\right)$.

C.E igenbeamformer

From (3) it follows that in order to keep the desired SNR at ther eceiver while trying to minimizet het ransmit power, the base station should use such weight vector, so that $\left|\mathbf{w}_D^{(\ell)H}\mathbf{h}\right|^2$ is maximized. Optimally it should be chosen according to $\mathbf{w}_D^{(\ell)}=\mathbf{h}/\|\mathbf{h}\|$, but since $\mathbf{h}$ is estimated at the mobile station and the capacity of the feedback channeli s very limited (1500 bps in WCDMA), only a rough approximation of $\mathbf{h}/\|\mathbf{h}\|$ can be signaled. Usually, $\mathbf{w}_D^{(\ell)}$ is chosen from a small predefined set of permitted weight vectors, which makes it possible to keep the feedback delay short and follow fast fading at low and medium mobile station speeds.

In downlink eigenbeamforming, long-term term channel properties are analyzed in order to tune the set of allowed vectors. This analysis comprises estimation of an average long-term spatial covariance matrix andp erformingi ts eigenvalue decomposition:

$$\mathbf{R}_h=E\{\mathbf{h}\mathbf{h}^H\}=\mathbf{V}\mathbf{\Lambda}\mathbf{V}^H \quad (5)$$

If one of the eigenvectors $\mathbf{v}_i$ (after complex conjugation) is used as an antenna weight vector, the mobile station would receive the signal with a mean received power proportional to the corresponding eigenvalue λ_i. Additionally, the fading of the received signal is uncorrelated between eigenvectors. These properties make the eigenvectors corresponding to the dominant eigenvalues an excellent set of allowed weight vectors, guaranteeing high received power and high diversity order.

Since in many cases the channel is correlated, it is enough to choose only between the two dominant eigenvectors, $\mathbf{v}_1$ and $\mathbf{v}_2$. One feedback bit is then sufficient to perform the selection, and in effect very short feedback delay and good performance even at high mobile speeds are achieved [3].

Clearly, the feedback commands must have exactly the same meaning for mobile station and for base station, and so the former must explicitly inform the latter about the dominant eigenvectors. Since itc an be assumed that the spatial correlation properties change slowly, $\mathbf{R}_h$ and its eigenvectors remain stable for several frames. To describe two eigenvectors with sufficient quality, approximately 50 bits are needed for a four-antenna system. In order to provide additional error protection for them, a rate 1/2 block code can be used. The coded bits are transmitted over the feedback channel in every 15th slot (i.e. oneb it per frame), and so the complete update takes approximately one second.

III. ANTENNA WEIGHT VERIFICATION

A.D edicated channel estimation

In order to perform symbol detection (and maximal ratio combining in case of multiple taps) for the dedicated channel isolated in (3), it is necessary to estimate the coefficient a accompanying the usable signal (indices ℓ dropped for shorter notation):

$$y_D(i)=a\cdot s_D(i)+n_D(i), \quad (6)$$

$$a=\sqrt{P_D}\,\mathbf{w}_D^H\mathbf{h}. \quad (7)$$

The preferred way of estimating a is by combining CPICH-based channel estimatesw ith the weight vector $\mathbf{w}^*_{req}$ requested through the feedback channel:

$$\hat{a}_{\mathrm{CPICH}} = \sqrt{P_{\mathrm{D}}}\,\mathbf{w}_{\mathrm{req}}^{H}\hat{\mathbf{h}} = \sqrt{P_{\mathrm{D}}}\,\mathbf{w}_{\mathrm{req}}^{H}\mathbf{h} + n_{\mathrm{CPICH}}, \tag{8}$$

$$n_{\mathrm{CPICH}} \sim \mathcal{N}_{\mathrm{C}}\left(0, \sigma^{2}\cdot SF_{\mathrm{C}}^{-1}P_{\mathrm{D}}P_{\mathrm{C}}^{-1}\right). \tag{9}$$

The main advantage of this method is a very low variance of additive Gaussian estimation error. Unfortunately, each time a feedback error occurs, the weight vector assumed by the mobile station is different from the vector actually used by the base station. In most of the cases this leads to detection with 50% Bit Error Rate (BER).

Alternatively, pilot symbols in Dedicated Physical Control Channel (DPCCH)c an be used fore stimation of a . The quality of such estimate is independent of feedback errors, but the variance of estimation error is considerably larger:

$$\hat{a}_{\mathrm{DPCCH}} = \sqrt{P_{t}}\,\mathbf{w}_{\mathrm{D}}^{H}\mathbf{h} + n_{\mathrm{DPCCH}}, \tag{10}$$

$$n_{\mathrm{DPCCH}} \sim \mathcal{N}_{\mathrm{C}}\left(0, \sigma^{2}\cdot SF_{\mathrm{D}}^{-1}N_{\mathrm{pilot}}^{-1}\right). \tag{11}$$

Neither of the two above estimates alone can guarantee reliable signal detection. It is possible,h owever,t o combine both of them in a process called antenna weight verification and obtain one reliable estimate.

B. MAP verification for eigenbeamformer

Without loss of generality, let us assume that the mobile station has informed the base station to use the eigenvector $\mathbf{v}_1$ for transmission of its dedicated channel. If the feedback bit was delivered without an error (with probability $1-P_e$) then the correct signal coefficient is a_{OK}. Otherwise (with probability P_e) $\mathbf{v}_2$ was used and the correct coefficient is a_{Err}:

$$a_{\mathrm{OK}} = \sqrt{P_{\mathrm{D}}}\,\mathbf{v}_{1}^{H}\mathbf{h}, \tag{12}$$

$$a_{\mathrm{Err}} = \sqrt{P_{\mathrm{D}}}\,\mathbf{v}_{2}^{H}\mathbf{h}. \tag{13}$$

The values a_{OK} and a_{Err} can be estimated at the mobile station according to (8),a nd together with the feedback error probability P_e (which is usually assumed to be equal 4%) they constitute an a priori probability distribution of a. If the DPCCH-based estimate is considered as an additional noisy measurement, it is possible to construct maximum a posteriori probability (MAP) estimate according to:

$$\hat{a}_{\mathrm{MAP}} = \underset{a\in\{a_{\mathrm{OK}},a_{\mathrm{Err}}\}}{\arg\max}\, P\left(a \mid \hat{a}_{\mathrm{DPCCH}}\right) = \underset{a\in\{a_{\mathrm{OK}},a_{\mathrm{Err}}\}}{\arg\max}\left(\ln p\left(\hat{a}_{\mathrm{DPCCH}} \mid a\right) + \ln P(a)\right), \tag{14}$$

where the probability density function of DPCCH-based estimate follows directly from (10):

$$p\left(\hat{a}_{\mathrm{DPCCH}} \mid a\right) = \frac{1}{\pi\sigma^{2}SF_{\mathrm{D}}^{-1}N_{\mathrm{pilot}}^{-1}}\exp\left(-\frac{\left|a-\hat{a}_{\mathrm{DPCCH}}\right|^{2}}{\sigma^{2}SF_{\mathrm{D}}^{-1}N_{\mathrm{pilot}}^{-1}}\right). \tag{15}$$

Analogously to (14), mobile station should assume that a feedback error took place whenever the following log-likelihood condition is fulfilled:

$$\ln\frac{p\left(\hat{a}_{\mathrm{DPCCH}} \mid a=a_{\mathrm{OK}}\right)}{p\left(\hat{a}_{\mathrm{DPCCH}} \mid a=a_{\mathrm{Err}}\right)} < L, \tag{16}$$

where $L = \ln P_e - \ln(1-P_e)$. Further transformations yield

$$\left|\hat{a}_{\mathrm{DPCCH}} - a_{\mathrm{Err}}\right|^{2} - \left|\hat{a}_{\mathrm{DPCCH}} - a_{\mathrm{OK}}\right|^{2} < \sigma^{2}SF_{\mathrm{D}}^{-1}N_{\mathrm{pilot}}^{-1}\cdot L, \tag{17}$$

as a practical criterion, ready to be evaluated at the mobile station[1].

IV.P ERFORMANCE OF ANTENNA WEIGHT VERIFICATION

A.E ffectiveness of MAP

In order to evaluate the performance of antenna weight verification it is necessary to calculate the probability of incorrect estimate after verification. To obtain the analytical result, the error detection criterion needs to be further transformed into form:

$$2\,\mathrm{Re}\left\{\frac{\frac{1}{2}\left(a_{\mathrm{Err}}+a_{\mathrm{OK}}\right)-\hat{a}_{\mathrm{DPCCH}}}{a_{\mathrm{Err}}-a_{\mathrm{OK}}}\right\} < \frac{\sigma^{2}SF_{\mathrm{D}}^{-1}N_{\mathrm{pilot}}^{-1}}{\left|a_{\mathrm{Err}}-a_{\mathrm{OK}}\right|^{2}}\cdot L. \tag{18}$$

By performing following substitutions:

$$\Delta = \frac{\left|a_{\mathrm{Err}}-a_{\mathrm{OK}}\right|}{\sqrt{\sigma^{2}SF_{\mathrm{D}}^{-1}N_{\mathrm{pilot}}^{-1}}}, \tag{19}$$

$$b = \Delta\cdot\mathrm{Re}\left\{\frac{\frac{1}{2}\left(a_{\mathrm{Err}}+a_{\mathrm{OK}}\right)-\hat{a}_{\mathrm{DPCCH}}}{a_{\mathrm{Err}}-a_{\mathrm{OK}}}\right\}, \tag{20}$$

this condition can be written as:

$$b < \tfrac{1}{2}\Delta^{-1}L. \tag{21}$$

Note that Δ is a normalized distance between the two candidate values for the estimate, and b follows real-valued Gaussian distributions:

$$p\left(b \mid a=a_{\mathrm{OK}}\right) = \mathcal{N}\left(\tfrac{1}{2}\Delta, \tfrac{1}{2}\right), \tag{22}$$

$$p\left(b \mid a=a_{\mathrm{Err}}\right) = \mathcal{N}\left(-\tfrac{1}{2}\Delta, \tfrac{1}{2}\right), \tag{23}$$

which are illustrated in Figure 1.

The estimate after verification is incorrect in two cases: when feedback error occurred butw as notd etected, or when there was no feedback error but (21) was satisfied. This fact is captured in the following formula:

$$P_{MAP}\left(\Delta,P_e\right) = P\left\{\hat{a}_{MAP}\neq a\right\} = P_e\cdot\tfrac{1}{2}\mathrm{erfc}\left(\tfrac{1}{2}\Delta+\tfrac{1}{2}\Delta^{-1}L\right) + \left(1-P_e\right)\cdot\tfrac{1}{2}\mathrm{erfc}\left(\tfrac{1}{2}\Delta-\tfrac{1}{2}\Delta^{-1}L\right) \tag{24}$$

Clearly, given certain feedback error probability P_e, the estimation error probability after verification depends exclusively on the hypothesis distance Δ.

[1] In fact, CPICH-based estimates need to be used in place of the exact values of a_{OK} and a_{Err}.I t is however assumed, that the estimates are highly reliable.

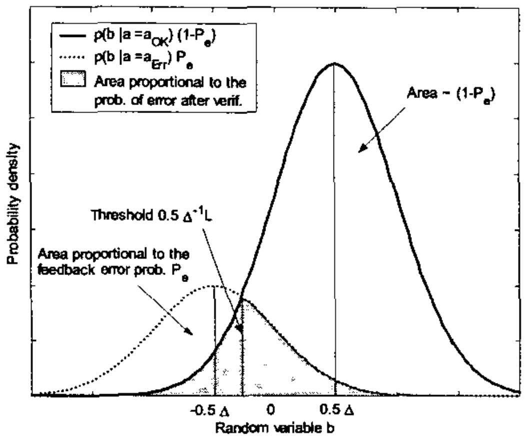

Figure 1: The principle of MAP antenna weight verification.

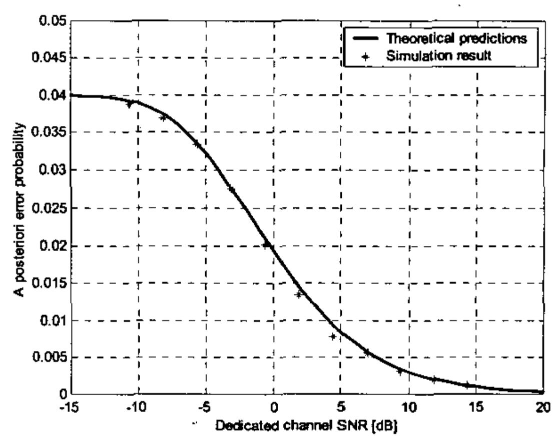

Figure 2: Estimation error probability after antenna weight verification with $N_{pilot} = 2$ pilot symbols,m obile speed of 10 km/h, and $P_e = 4\%$ feedback error rate.

B. Hypothesis distance distribution

The distance Δ is not a constant, but depends on the current realization of the channel**h** and the transmission power P_D used. In ordert o determine the average estimation error probability it is necessary to describe Δ in terms of its probability density function. From (12)a nd (19)i t follows that the performance of power control (which controls the relation between **h** and P_D) affects this distribution. Since realistic power control is difficult to model,a simplifying assumption of slow power control can be taken,i .e. P_D is assumed to be constant as channel varies.

By realizing the fact that a_{OK} and a_{Err} follow zero-mean complex Gaussian distribution with variances $P_D\lambda_1$ and $P_D\lambda_2$ and are uncorrelated, theΔ must follow the Rayleigh distribution. Thereforei ts probability density function can bee xpressed as follows:

$$p(\Delta) = 2\frac{\Delta}{\sigma_\Delta^2}\exp\left(-\frac{\Delta^2}{\sigma_\Delta^2}\right), \tag{25}$$

$$\sigma_\Delta^2 = \frac{P_D(\lambda_1 + \lambda_2)}{\sigma^2 SF_D^{-1} N_{pilot}^{-1}}. \tag{26}$$

By assuming that feedback error probability is small enough not to affect the mean signal power,(26) can be written as:

$$\sigma_\Delta^2 = SNR_D \cdot N_{pilot}, \tag{27}$$

where SNR_D is the average signal-to-noise ratio in the despread dedicated channel. The final predicted value of estimation error probability is calculated by integrating numerically:

$$E\{P_{MAP}\} = \int_0^{+\infty} P_{MAP}(\Delta)p(\Delta)d\Delta. \tag{28}$$

C.O verall performance

The relation between the signal-to-noise ratio in the dedicated channel and probability of wrong assumption about used weight vector (probability of estimation error) is depicted in Figure 2 for feedback error rate (P_e) of 4%. The solid line represents the values obtained with (28). It can be seen that at very low SNR values the estimation errorp robability remains at 4%, since the DPCCH-based estimate is not reliable enough to provide information for the estimator. However, as the SNR increases, this probability decreases and tends asymptotically to zero. This effectively means, that antenna weight verification is capable of eliminating the error floor effect, i.e., the bit (frame) error rate does not saturate with increasing signal power.

Along theoretical results, Figure 2 includes estimation error rates obtained by link-level simulation. Despite the simplification of slow power control the results match very well with the results of our analysis.

V.S IMULATION RESULTS

The performance ofc losed-loop downlink eigenbeamforming for spatially uncorrelated (all eigenvalues of $\mathbf{R}_b$ equal) and partially correlated ($\lambda_{1,2,3,4}$ = 0.54, 0.36, 0.09, 0.01) channel is illustrated in Figure 3. The figure of merit is the energy per chip for one user (E_C) divided by the total base station power (I_{OR}), required to reach the frame error rate (FER) of 1%.

If the dedicated channele stimation is based solely on CPICH, then the performance degradation caused by feedback errors is very large. Att he operating point of 1% Frame Error Rate (FER) this means over 5 dB of E_C/I_{OR} loss in both considered scenarios. The clearlyv isible error floor makes the FER values below about 0.5% unachievable for any reasonable E_C/I_{OR} value.

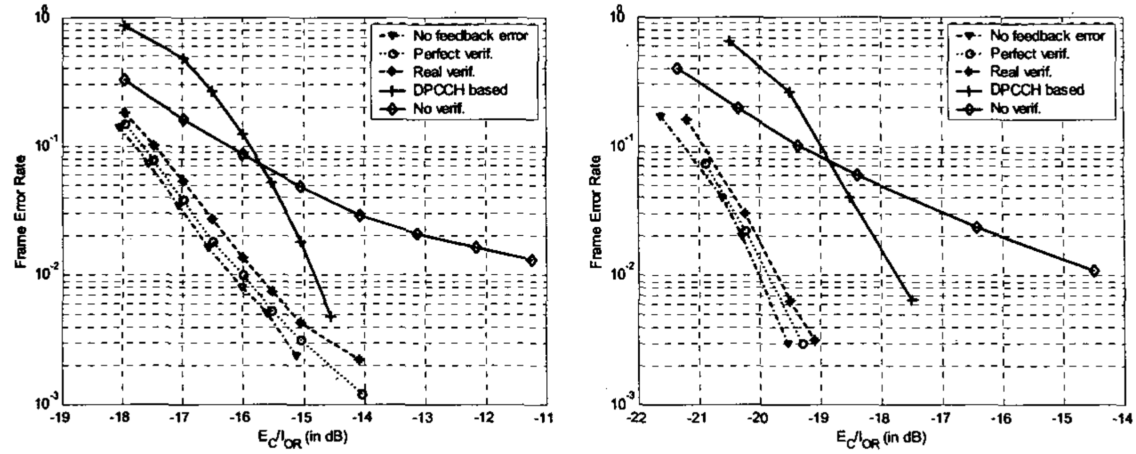

Figure 3: Frame Error Rate performance for spatially uncorrelated (left) and partially correlated (right) scenario, speed 10 km/h, Pedestrian A [8], $P_e = 4\%, N_{pilot} = 2$, 4 antennas.

If we provide the mobile station with ability to know (with a help of a genie) whether base station received the feedback bit correctly or not (perfect verification), then no estimation error is present. In such case, the performance loss compared to the no-feedback-error case is very small, about 0.2 dB in both scenarios. It is interesting to note that if no antenna verification is used, it is actually better to use the channel estimation based solely on DPCCH pilot symbols since it does not experience the error floor. The E_C/I_{OR} difference to the perfect verification case is 1.2 dB for uncorrelated, and 2.1 dB for the partially correlated scenario.

Finally, if antenna weight verification is employed at the mobile station, the estimation error caused by feedback error is almost completely suppressed. Compared to ideal verification (which is the lower bound on the verification performance), it loses only 0.2 dB at 1% FER in both analyzed scenarios. As expected,t he error floor is not present.

VI.C ONCLUSIONS

Closed-loop downlink beamforming relies on the operation of the feedback channel. Feedback errors lead to an unavoidable, yet small, performance loss caused by usage of suboptimal antenna weight vector. Additionally, if mobile station relies on the common pilot channel for dedicated channel estimation and ignores the risk of a feedback error, it faces huge performance degradation in the form ofe rror floore ffect. The lattere ffect is much more severe, but it can be reduced with a help of antenna weight verification.

Within this paper, an antenna weight verification scheme for downlinke igenbeamformer has been derived based on MAP hypothesis testing. Since for eigenbeamformer there are only two possible weight vectors in each slot, the processing necessary for performing the verification is kept simple. At the same time, such low number of hypothesese nsuresh igh mean distance between them, leading to excellent error detection performance.

It has been demonstrated by theoretical investigation and link-level simulations that the antenna weight verification eliminates the error floor effect and minimizes the performance degradation. In effect, antenna weight verification needs to be considered as an integral part of the downlink eigenbeamformer.

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