Predicting SINR conditions in mobile MIMO-OFDM systems by interpolation techniques

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***Abstract*—Channel adaptive transmission in multi-user MIMO systems is seen as a promising concept to achieve high spectral efficiencies in future radio networks: Based on feedback on actual channel conditions, the base station allocates transmission resources to the user terminals where they can support high data rates. However, due to the delay between evaluation of the channels at the terminals and application of the resource allocation decision, the concept operates conveniently only under quasi-static channel conditions. In case user terminals are moving, the channel may vary and thus the adaptive concept may suffer strong performance degradations. For a channel-adaptive transmission concept based on evaluation of SINR conditions, we propose a solution to predict future SINR conditions based on channel interpolation techniques. For a limited prediction interval depending on the receive antenna spacing, the technique significantly diminishes potential SINR losses.**

I. Introduction

Channel adaptive transmission combined with multiple antenna technology (MIMO) is seen as a promising concept to achieve high spectral efficiencies in future radio networks [1], [2]. While MIMO enables to transmit multiple data streams on the same frequency resource, the channel adaptive concept enables to conveniently utilize the capabilities of the channel by forming precoding vectors matched to the MIMO channel as well as adapting the data rate to the current SINR conditions. The basic idea of adaptivity is that the user terminals (UTs) provide feedback on their actual channel conditions to the base station (BS) [3]. This information is used at the BS within a resource allocation process to assign the transmission resources to the UTs where high data rates can be supported. A simplified practical approach for the adaptive MIMO downlink with low demands on feedback is to let the BS provide a set of fixed precoding vectors. These are evaluated at the UTs by determining adequate reception SINRs, which are then fed back to the BS (Grid of Beams concept, see [2]). Feedback and resource allocation cause a delay between SINR determination and the final application of the resource assignment decision. Thus, this assignment may be considered useful only if the channel behaves quasi-static. However, in case the UTs are moving fast, the predetermined SINR conditions may drop down, resulting in severe performance degradations of the system. Therefore, it would be desirable to modify the system concept accordingly to account for the temporal evolution of the channel and thus enable application of the channel-adaptive concept also in a mobile scenario.

For the channel-adaptive MIMO-OFDM system concept presented in [4], we examine the SINR degradation affecting the system under time-varying channel conditions. To mitigate these degradations, we then develop an approach that relies on channel interpolation techniques [5] to predict the SINRs for a future time instant where the resource assignment decision is expected to be applied. Examination of the SINR degradations based on the predicted channels reveals that the technique is capable of diminishing the potential SINR losses significantly.

II. Signal model

We consider downlink transmission in a MIMO-OFDM system, where the BS transmits an OFDM signal from N_t antennas to a UT equipped with N_r antennas. Transmission is based on a radio frame structure, where each frame is constituted of several consecutive OFDM symbols. For the duration of a radio frame, coherent data signals are contained in frequency subbands confined to a fixed number of consecutive subcarriers, called *chunks*. The transmission equation for a single subcarrier signal in a chunk received by the terminal in OFDM symbol i is given by

$$\mathbf{r}(i) = \mathbf{H}(i)\mathbf{C}\mathbf{x}(i) + \mathbf{n}(i) \tag{1}$$

where $\mathbf{x}(i)$ is the vector of N_t transmit symbols with mean power P_s, $\mathbf{r}(i)$ is the N_r-dimensional receive vector and $\mathbf{n}(i)$ is the vector of N_r AWGN noise samples with mean power N_0. $\mathbf{C}$ is a precoding matrix comprising N_t fixed beams $\mathbf{c}_n$ with unitary property. The $N_r \times N_t$ channel matrix will be partitioned according to

$$\mathbf{H}(i) = [\mathbf{h}_1(i) \cdots \mathbf{h}_{N_t}(i)] \tag{2}$$

where each column vector $\mathbf{h}_n(i)$ represents the N_r-dimensional channel between n-th transmit antenna and the receive antenna array.

According to the concept presented in [4], the UT can evaluate the post-detection SINRs for the data streams transmitted via the beams $\mathbf{c}_n, n \in \{1, \ldots, N_t\}$, contained in $\mathbf{C}$. Two spatial transmission modes are supported, namely single-stream (ss) and multi-stream (ms) mode, allowing to switch between the number of beams Q which are simultaneously active. The total transmit power P_s is distributed uniformly over these active beams Q. Assuming a linear receiver $\mathbf{w}_n$, the achievable post-detection SINR for the signal transmitted on n-th beam $\mathbf{c}_n$ for any transmission mode can be determined

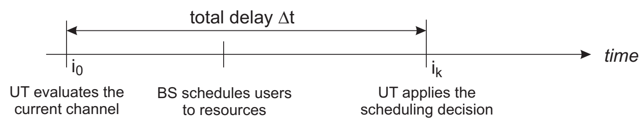

Fig. 1. Delay occurring in a practical system between channel evaluation and application of the resource allocation.

at the UT according to

$$\mathrm{SINR}(\mathbf{c}_n) = \frac{\|\mathbf{w}_n^H \mathbf{H}\mathbf{c}_n\|^2}{\mathbf{w}_n^H \mathbf{Z}_n \mathbf{w}_n}, \quad (3)$$

$$\mathbf{Z}_n = \sum_{j=1, j\neq n}^{Q} \mathbf{c}_j \mathbf{H}\mathbf{H}^H \mathbf{c}_j^H + \frac{QN_0}{P_s}\mathbf{I}$$

where $(\cdot)^H$ is the conjugate transpose operator and $\mathbf{I}$ is the identity matrix. The optimum combining solution for $\mathbf{w}_n$ is given as [6]

$$\mathbf{w}_n = \varepsilon \mathbf{Z}_n^{-1} \mathbf{H}\mathbf{c}_n \quad (4)$$

with scaling factor ε. Having evaluated the post-detection SINR for the different supported spatial modes, the UT feeds back this information to the BS, which then carries out the resource allocation and transmission mode selection and informs the UT on its decision.

III. SINR LOSS DUE TO CHANNEL'S TIME VARIANCE

In a practical system, evaluation of the SINRs at the UT will be carried out based on the channel measured at time instant i_0, while the scheduling decision will be applied at time instant $i_k > i_0$, resulting in a delay Δt, see Fig. 1. During this time, the channel may change, so that the SINR conditions measured at i_0 may no longer be valid. In case the SINR conditions in a scheduled resource drop down, the channel will be overloaded, which means a bit rate will be used in that resource that cannot be supported by the channel any longer. Hence, detection errors are very likely to occur, resulting in severe performance degradations. In particular, variations of the SINR conditions will take on effect if the delay Δt is in the order of the channel's coherence time T_c, which we define as $T_c = f_D^{-1}$, with f_D being the maximum Doppler frequency. For a fixed system configuration, Δt is in general a constant system parameter, and hence only the Doppler frequency f_D, which is invoked by the speed of the UT, impacts the SINR variations. This aspect will be focussed on in our first investigation, for which we set up the following framework:

The channel evaluation process is carried out by the UT to determine the achievable rates based on the actual channel at OFDM symbol index i_0. Once the SINRs have been determined for all available chunks and all supported transmission modes, we select per transmission mode half the chunks with best SINR values. This is done to account for the property of the scheduler used in [4], which tends to assign each UT its best chunks only. After the delay Δt, we end up at OFDM symbol index $i_k = i_0 + \Delta i$, with Δi being the number of

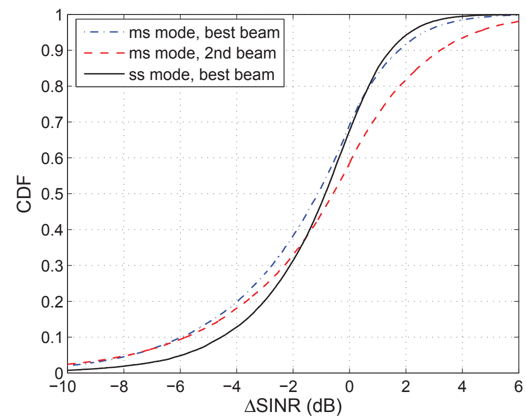

Fig. 2. CDF of the deviation of per-stream SINR for the different transmission modes ms and ss. $\Delta t = 0.2T_c$.

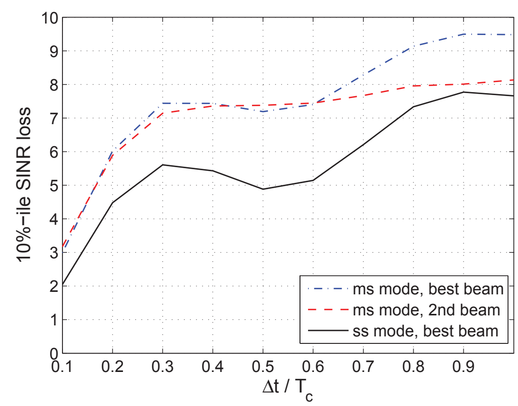

Fig. 3. Loss of the per-stream SINR (in dB) for the 10-percentile of the ΔSINR-CDF vs. channel dynamics.

OFDM symbols spanning the duration of the delay Δt. Based on the altered channel $\mathbf{H}(i_k)$, we recalculate the SINR values for the selected chunks per mode and determine the difference ΔSINR to the original SINR values based on $\mathbf{H}(i_0)$, which represents our evaluation measure.

We focus on a 2×2 MIMO configuration supporting ss ($Q = 1$) and ms ($Q = 2$) transmission mode for our investigations. The precoding matrix $\mathbf{C}$ consists of the two beams $\mathbf{c}_1 = [1\, j]^T$ and $\mathbf{c}_2 = [1\, -j]^T$, which are derived from the DFT matrix [7]. We use the WIM channel model [8] in its wide-area configuration, with transmit antenna spacing set to 4λ and receive antennas spacing to 0.5λ. For the evaluation, we assume constant mean SNR conditions characterized by $P_s/N_0 = 10$dB. Fig. 2 shows the cumulative distribution function (CDF) of ΔSINR (measured in dB) for the streams of the different transmission modes for channel dynamics characterized by $\Delta t = 0.2T_c$. In each chunk, the two streams of ms mode have been ordered by the quality of their SINR. Note that only negative values of ΔSINR translate into a loss of the measured SINR value and thus may result in

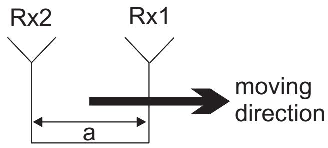

Fig. 4. Configuration of the linear antenna array used for the prediction-based approach.

a performance degradation. From Fig. 2, we observe that the median value of ΔSINR is negative, which means that the SINR conditions in the selected chunks tend to drop down. Further, we observe that all CDFs exhibit a broad left tail. From these observations, we conclude that severe SINR degradations are likely to occur, which may have a negative impact on the system performance. Obviously, the two beams of the ms mode suffer the most from SINR degradations, while the beam in ss mode suffers least, as the left tail of its corresponding CDF lies significantly below the ones of the two beams in ms mode.

In Fig. 3 we depict the 10-percentile of the ΔSINR-CDF for variable channel dynamics $\Delta t/T_c$. For all spatial beams, we observe that the SINR loss rises steeply with increasing channel dynamics up to $\Delta t = 0.3T_c$, revealing a high sensitivity of the measured SINR conditions towards the time variances of the channel. Again, we observe here that the beam in ss mode suffers the least from SINR losses over the considered dynamic range.

IV. Predicting SINR conditions by channel interpolation techniques

To alleviate the effect of SINR degradations, it would be desirable to predict the channel state at time instant $i_k = i_0 + \Delta i$ at the UT and carry out the channel evaluation process based on that channel, $\mathbf{H}(i_k)$. In this section, we develop such a channel prediction approach based on linear channel interpolation techniques [5], which relies on a specific arrangement of the receive antenna array.

As variations of the channel $\mathbf{H}(i)$ over the duration Δt become significant rather at vehicular speeds, it is reasonable to assume that the receive antennas of the mobile terminal can be mounted at a fixed position on the moving vehicle. We assume the antennas to be arranged as a uniform linear array with fixed antenna spacing, with its broadside oriented in the moving direction (see Fig. 4) – an idea which has already been presented in [9]. With this configuration, the channel seen at receive antenna 2 (Rx2) is a delayed version of the one seen at Rx1. The delay D, measured in integer numbers of OFDM symbols, depends on the spacing a of the two antennas as well as on the vehicle's moving speed. The channel vector for n-th transmit antenna can thus be given as

$$\mathbf{h}_n(i) = [h_n(i) \;\; h_n(i-D) \; \cdots \; h_n(i-(N_r-1)D)]^T \qquad (5)$$

According to this notation, the channel vector $\mathbf{h}_n(i)$ contains N_r equi-spaced sampling points of the time-variant channel function $h_n(i)$.

A. Statistical properties of the channel vectors

We will now characterize the statistical properties of the channel vectors $\mathbf{h}_n(i)$. We consider all channel functions $h_n(i)$, $n \in \{1, \ldots, N_t\}$, constituting those vectors to have identical statistics. Hence, we focus on a channel for a single transmit antenna and omit the index n for notational convenience.

The channel's autocorrelation function (ACF) is given as $\varphi_{hh}(k) = E\{h(i)h^*(i+k)\}$. Assuming Jakes' model for the temporal evolution of the channel function $h(i)$, the autocorrelation function yields [10]

$$\varphi_{hh}(k) = E\{h(i)h^*(i+k)\} = J_0(2\pi k f_D \cdot T_o) \qquad (6)$$

$J_0(\cdot)$ is the the Bessel function of the first kind resulting from Jakes' Doppler power spectrum, and T_o is the OFDM symbol duration. The covariance matrix of the channel vector $\mathbf{h}(i)$ is defined as

$$\mathbf{R}_{hh} = E\{\mathbf{h}(i)\mathbf{h}^H(i)\}$$

Using (5), its elements can be related to the ACF φ_{hh} according to

$$[\mathbf{R}_{hh}]_{cd} = \varphi_{hh}((d-c)D) = J_0(2\pi(d-c)Df_D \cdot T_o) \qquad (7)$$

where $[\mathbf{R}_{hh}]_{cd}$ represents the element of matrix $\mathbf{R}_{hh}$ found in c-th row and d-th column. The delay D can be related to the antenna spacing a and the speed v of the mobile vehicle according to $DT_o = a/v$. Further, v relates to the Doppler frequency f_D via $v = f_D\lambda$, with λ being the wavelength of the carrier frequency. Thus, we obtain

$$D = \frac{a}{\lambda f_D T_o} \qquad (8)$$

Inserting this expression into (7), we obtain for the elements in the correlation matrix $\mathbf{R}_{hh}$

$$[\mathbf{R}_{hh}]_{cd} = J_0(2\pi(d-c)a/\lambda) \qquad (9)$$

B. Channel prediction by linear interpolation techniques

As the channel vector $\mathbf{h}(i_0)$ according to (5) supplies N_r equi-spaced sampling points of the channel function $h(i)$, we can use channel interpolation techniques to determine $h(j)$ for an arbitrary j and thus obtain an estimate for the channel vector $\mathbf{h}(i_k)$ for a future time instant $i_k > i_0$. However, for proper application of the interpolation techniques, it has to be ensured that the density of sampling points of $h(i)$ obtained from the vector $\mathbf{h}(i)$ complies to the requirement of the sampling theorem, which yields [5]

$$2f_D DT_o \leq 1 \quad \Leftrightarrow \quad a \leq \lambda/2$$

where we used equation (8). From this result we can conclude that the channel prediction based on channel interpolation techniques requires an antenna spacing of at least $\lambda/2$.

Next we turn our focus on the realization of the channel predictor. Note that the interpolation-based prediction gets the more reliable, the more information on the channel function $h(i)$ can be taken into account. Hence, we use the measured channels $\mathbf{h}_n(i)$ gathered over a complete transmission frame consisting of N_f successive OFDM symbols, i.e. $i \in \{-N_f+1,\dots,0\}$ as input for the predictor. We assume here that $i_0 = 0$ is the index of the last OFDM symbol in the transmission frame under consideration (see Fig. 5). Let

$$\mathbf{y}_m = [h(-(m-1)D - N_f + 1) \cdots h(-(m-1)D)]^T \quad (10)$$

be a vector comprising the N_f successive observations of the channel coefficient at m-th receive antenna. A compound observation vector is formed by stacking the single vectors $\mathbf{y}_m$ into one according to their temporal order, i.e. $\mathbf{y} = [\mathbf{y}_{N_r} \cdots \mathbf{y}_1]^T$. The minimum mean square error (MMSE) solution of the linear interpolator [5] yields for the estimate of the future channel vector $\hat{\mathbf{h}}(i_k)$

$$\begin{aligned} \hat{\mathbf{h}}(i_k) &= \theta^H(i_k)\Phi^{-1}\mathbf{y} \quad (11)\\ \theta(i_k) &= E\{\mathbf{y}\mathbf{h}^H(i_k)\}\\ \Phi &= E\{\mathbf{y}\mathbf{y}^H\} + \gamma^{-1}\mathbf{I}_{N_r K} \end{aligned}$$

where γ is the SNR of the measured channels contained in $\mathbf{y}$. The matrix $E\{\mathbf{y}\mathbf{y}^H\}$ constituting Φ can be structured into submatrices $\mathbf{A}_{mj}$ of dimension $N_f \times N_f$, which result from the outer products of the subvectors in $\mathbf{y}$, i.e. $\mathbf{A}_{mj} = E\{\mathbf{y}_m\mathbf{y}_j^H\}$. Their elements relate to the channel's ACF $\varphi_{hh}(k)$ according to

$$[\mathbf{A}_{mj}]_{cd} = \varphi_{hh}((j-m)D + (d-c))$$

Correspondingly, the matrix $\theta(i_k)$ can be structured into submatrices $\mathbf{B}_m = E\{\mathbf{y}_m\mathbf{h}^H(i_k)\}$ of dimension $N_f \times N_r$, whose elements relate to the ACF as

$$[\mathbf{B}_m]_{cd} = \varphi_{hh}(-(m-d)D - k + c)$$

Once we have obtained the predicted channel vectors $\hat{\mathbf{h}}_n(i_k)\ \forall n \in \{1,\dots,N_t\}$ from (11), we can construct the predicted channel matrix $\hat{\mathbf{H}}(i_k)$ according to (2). Based on this matrix, the UT can then determine the SINRs for the different spatial modes according to (3).

C. Evaluation of the prediction-based approach

To evaluate the potential of the channel prediction approach, we carry out similar investigations as performed in section III based on the same system conditions. The frame length is set to $N_f = 20$ OFDM symbols. The delay between the last channel sample measured in the current frame and the predicted one amounts $\Delta i = 4N_f$, i.e. the duration of 4 complete frames. Evaluations are carried out for an SNR $P_s/N_0 = 10$dB; the SNR of the measured channels used in (11) is set to $\gamma = 20$dB. Thus, γ lies 10dB above the SNR, which means we implicitly assume an estimator gain of 10dB. Such an estimator gain is achievable if sophisticated channel estimation techniques are applied [11]. The ACF φ_{hh} of the channels for the single transmit/receive antenna links is assumed to be ideally known.

Results from numerical evaluations are given in Fig. 6-8. Fig. 6 shows the CDFs of ΔSINR per spatial stream in the ss and ms mode based on the predicted channels $\hat{\mathbf{H}}(i_k)$. For comparison, we also added the CDF for ss mode from Fig. 2 as solid grey line, which is based on $\mathbf{H}(i_0)$. We clearly observe that the prediction-based approach results in CDF curves with significantly steeper slopes than the curves based on $\mathbf{H}(i_0)$, which means that the variance of ΔSINR is significantly decreased. Further, we observe that the median value of ΔSINR is positive now, i.e. the SINR conditions do not tend to drop down any longer. Regarding the left tail of the CDFs reveals that the probability of high SINR losses to occur is significantly reduced. The curve of ss mode exhibits the steepest slope, indicating that this mode is still the one which suffers the least from SINR degradations.

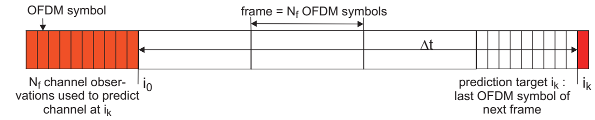

Fig. 5. Frame structure used for the prediction-based approach.

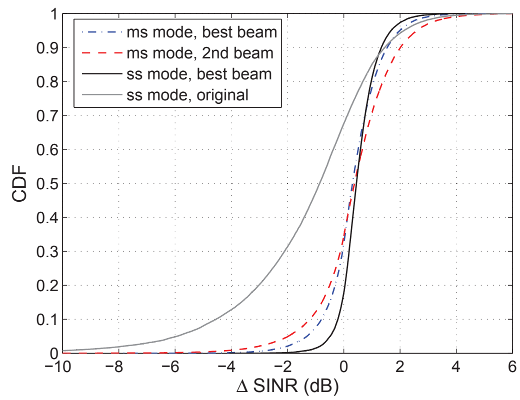

Fig. 6. CDF of the deviation of per-stream SINR for the different transmission modes ms and ss. $\Delta t = 0.2T_c$, prediction-based approach

Obviously, there is a price we have to pay for the improved stability of the SINR conditions for the different beams. This is revealed in Fig. 7, where we depict the median SINR values determined for $\hat{\mathbf{H}}(i_k)$ versus the channel dynamics: As the channel gain for the first receive antenna Rx1 is effectively obtained by an extrapolation through (11), the channel predictor tends to underestimate the channel, which translates into a drop of the median achievable SINR with increasing channel dynamics. However, for $\Delta t < 0.5T_c$, this drop is rather small and amounts to not more than 2dB for $\Delta t = 0.5T_c$.

For $\Delta t > 0.5T_c$, however, the slope of the curves representing the SINR drop increases significantly for the beams supported in ms mode. This effect can be explained as follows: Note that the second entry of the channel vector $\mathbf{h}_n(i_k)$ according to (5) reads $h_n(i_k - D)$. The channel predictor (11) generates this entry from an interpolation between the entries of $\mathbf{h}_n(i_0)$, i.e. $h_n(i_0 - D)$ and $h_n(i_0)$, as long as the prediction interval fulfils $\Delta i = i_k - i_0 < D$. Substituting D

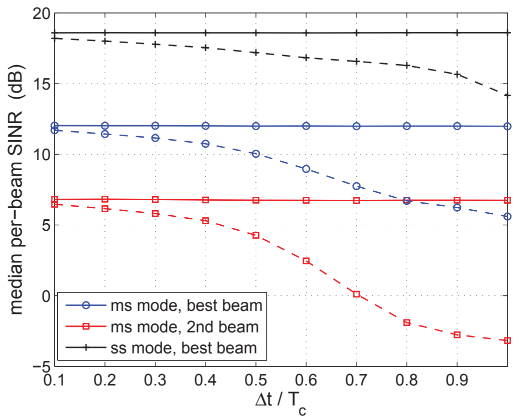

Fig. 7. Median SINR values from channel evaluation at UTs based on measured (solid curves) and predicted channels (dashed curves).

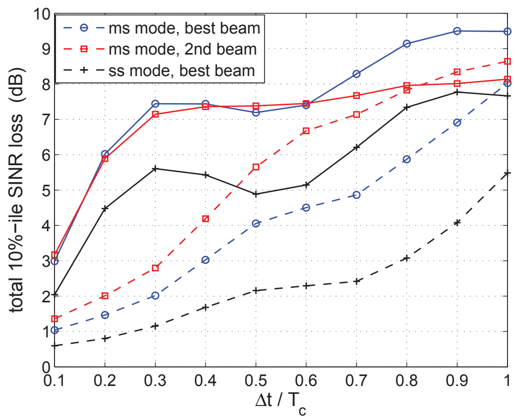

Fig. 8. Total loss of the per-stream SINR (in dB) for the 10-percentile of the ΔSINR-CDF measured (solid) and predicted channels (dashed).

with (8) in this relation, we yield

$$\Delta i T_o < \frac{a}{\lambda f_D} \quad \Leftrightarrow \quad \Delta t < \frac{a}{\lambda} T_c$$

If this relation holds, the second entry of $\mathbf{h}_n(i_k)$ is obtained from an interpolation, while it is extrapolated otherwise. It is well-known that an extrapolation yields less reliable results than an interpolation, and hence the overall signal conditions can be expected to degrade significantly in that case. As we used $a = 0.5\lambda$ here, this phenomenon can be clearly observed in Fig. 7 for $\Delta t > 0.5T_c$.

To account for the median SINR loss inherent to the channel prediction approach, we add the corresponding losses obtained from Fig. 7 (in dB) to the ΔSINR values obtained for each value of $\Delta t/T_c$. Fig. 8 depicts the 10-percentile of the corresponding ΔSINR-CDFs in comparison to the original curves shown in Fig. 2. We clearly observe here that for $\Delta t < 0.5T_c$, the SINR degradation increases much more smoothly than in the previous case. The reduction in the total SINR loss is between 3 and 4dB for this range of interest, indicating that the prediction-based approach is capable of diminishing SINR degradations substantially. Thus, the proposed approach can be seen as a promising concept to support channel adaptive transmission also in mobile environments.

V. Conclusion

We have focussed on the behaviour of the spatial adaptation concept presented in [4] in time-variant channel environments, where the UTs move at vehicular speeds. It has been shown that if the original concept is applied without alterations, the delay occurring between channel evaluation and application of the scheduling decision may cause the evaluated SINR to drop down substantially. This may result in severe degradations of the system performance. For a suitable configuration of the receive antenna array at the UTs, we proposed a concept to predict the channels for a future time instant based on linear interpolation techniques. These predicted channels can be used for the determination of the SINR values to improve their reliability. The prediction-based approach has been evaluated for the 2×2 system configuration. It has been shown that the estimated SINR values become much more stable and SINR losses can be significantly reduced, as long as the prediction interval remains within the limits dictated by the receive antenna spacing. These results let the prediction-based approach pave the way towards a beneficial application of the channel-adaptive MIMO transmission concept also in mobile environments.

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