Tran, T., Nix, A. R., & Doufexi, A. (2010). Mobile WiMAX: impact of mobility on the performance of limited feedback linear precoding. In IEEE 71st Vehicular Technology Conference 2010 (VTC 2010-Spring), Taipei, Taiwan. (pp. 1 - 5). Institute of Electrical and Electronics Engineers (IEEE). 10.1109/VETECS.2010.5494115

Mobile WiMAX: Impact of Mobility on the Performance of Limited Feedback Linear Precoding

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Abstract— **The mobile WiMAX standard (802.16e) uses multiple-input multiple-output (MIMO) limited feedback linear precoding to exploit the channel state information at the transmitter. Although the performance of limited feedback linear precoding in relation to traditional open-loop MIMO has been extensively studied in the literature, these studies commonly assume a zero-lag feedback channel. However, due to the mobile nature of the mobile station (MS), the channel feedback information at the base station (BS) is incorrect because of an inherent delay between the time the MS estimates the channel feedback information and the time it is used in the BS. This results in performance degradation compared to a zero-lag feedback channel. To date, few researchers have studied the impact of MS velocity and Doppler spread on the performance of limited feedback linear precoding. Simulation results show that the performance of the mobile WiMAX precoded system degrades significantly as the MS velocity increases. At a velocity of 3km/h the precoded system degrades by 0.1-0.2dB in terms of array gain. However, the performance drops considerably when the velocity exceeds 10 km/h. At high MS velocities (i.e., 120 km/h), the linear precoding technique fails to provide any benefits. In this high mobility case we show that a linear precoding MIMO system with more antennas experiences the same performance as an open-loop MIMO system with fewer antennas.**

Index Terms—**802.16e, WiMAX, MIMO, linear precoding.**

I. INTRODUCTION

The first WiMAX systems were based on the IEEE 802.16-2004 standard [1]. This targeted fixed broadband wireless applications via the installation of Customer Premises Equipment (CPE). In December 2005 the IEEE completed the 802.16e-2005 [2] amendment, which added new features to support mobile applications.

Mobile WiMAX now supports both open-loop and closed-loop multiple-input multiple-output (MIMO) techniques. Open-loop techniques, such as space time block coding (STBC) and spatial multiplexing (SM), can be used to increase diversity gain or system throughput without the need for channel state information (CSI) at the transmitter. However, recent work [3, 4] has reported further increases in system performance (both diversity and array gain) and throughput by applying linear precoding techniques at the transmitter that exploit knowledge of the CSI.

The key idea behind linear precoding is to customize the transmit signal by pre-multiplication with a precoding matrix. It is well-known that singular value decomposition (SVD) linear precoding provides the highest achievable performance [4]. However, the SVD approach requires perfect CSI at the transmitter, which cannot be achieved in a MIMO Mobile WiMAX system with numerous antennas, subcarriers, and a rapidly changing channel. The need to reduce the amount of CSI feedback information motivates the use of a codebook based linear precoding technique [5, 6]. Here, the mobile station (MS) calculates the optimal precoder matrix for each subcarrier and feeds back the matrix, rather than the CSI, to the base station (BS). Specifically, the optimal precoder matrix is constrained to one of N distinct matrices, which are referred to as codebook entries, designed offline and known to both the MS and BS. The MS identifies the optimal precoder matrix based on the current CSI. Since the codebook is known at the BS, the MS only needs to feedback a binary index of the optimal precoder matrix, rather than the entire precoder matrix itself. For each combination of the number of transmit (N_T) and receive (N_R) antennas, the 802.16e standard defines two codebooks: one with 8 entries and the other with 64 entries.

The performance improvement of codebook based linear precoding has been previously reported in the literature [5, 6]. However, results were often based on the assumption of an ideal zero-lag feedback channel. In a highly mobile environment with fixed feedback delay, the precoding matrix derived at the MS often becomes outdated before it is applied at the BS. This results in significant performance degradation. This paper evaluates the impact of MS mobility and feedback delay on the performance of a mobile WiMAX system with linear precoding.

The paper is organized as follows: Section II describes important parameters used in the mobile WiMAX simulator. An overview of precoded spatial multiplexing and dominant eigenbeamforming for mobile WiMAX systems is described in Section III. Delayed feedback in the context of a mobile WiMAX system is explained in Section IV. Section V investigates the impact of mobility, Doppler spread and feedback delay on the performance of a precoded mobile WiMAX system. Section VI discusses several techniques designed to mitigate the problems associated with mobility. Finally, conclusions are presented in Section VII.

II. LINK LEVEL MOBILE WIMAX SIMULATOR

A detailed downlink Mobile WiMAX link-level simulator [7] using the PUSC subcarrier permutation and convolutional coding with soft Viterbi decoding has been implemented by the authors based on the 802.16e-2005 standard [2]. The simulator models a cell with an omni-directional basestation (BS) and three mobile stations (MS) randomly situated in the cell. In the downlink, each MS is allocated 5 out of a total of 15 subchannels. The BS transmits data simultaneously to 3 MS, with each sharing a common OFDMA symbol. Table I summarises the OFDMA parameters used in the Mobile WiMAX simulator. A detailed description of the simulator can be found in [7].

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TABLE I: OFDMA PARAMETERS

Parameter	Value
Carrier frequency (GHz)	2.3
FFT size (N_{FFT})	512
Channel bandwidth (MHz)	5
Sampling frequency F_s (MHz)	5.6
Subcarrier frequency spacing $\Delta f = F_s/N_{FFT}$ (kHz)	10.94
Useful symbol period $T_b = 1/\Delta f$ (μs)	91.4
Guard Time $T_g = T_b/8$ (μs)	11.4
OFDMA symbol duration $T_s = T_g + T_b$ (μs)	102.9
Number of used subcarriers (N_{used})	421
Number of pilot subcarriers	60
Number of data subcarriers	360
Number of data subcarriers in each subchannel	24
Number of subchannels	15

Based on the ETSI 3GPP2 spatial channel model (SCM) [8], an urban micro tapped delay line (TDL) channel was generated for use in this analysis. The TDL comprises 6 taps with non-uniform delays. Each tap experiences Rayleigh fading based on an MS velocity and the traditional Jake Power Doppler Spectrum [9]. The antenna element separation is 10λ at the BS and 0.5λ at the MS, where λ represents the carrier wavelength.

III. LINEAR PRECODING

This section summarizes two different linear precoding systems, namely linear precoding spatial multiplexing (SM PRE) and dominant eigenbeamforming (DE), both of which are implemented in the mobile WiMAX simulator. For purposes of simplicity, a generic linear precoding system for a single subcarrier is illustrated in Fig. 1. For the SM PRE system the number of spatial streams $M \geq 2$, for the DE system $M=1$.

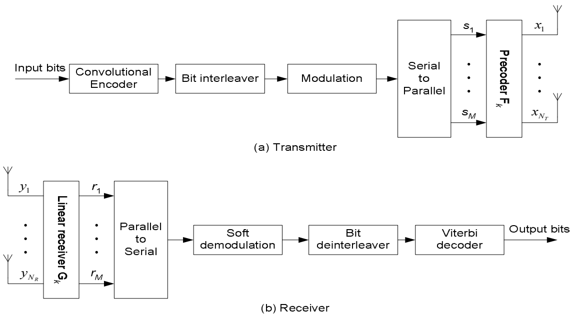

Fig. 1: Linear precoding spatial multiplexing system block diagram

A. Linear precoding spatial multiplexing (SM PRE)

In the case of an OFDM mobile WiMAX system, the k-th subcarrier is allocated a precoder matrix $\mathbf{F}_k$, and the $N_R \times 1$ receive symbol vector $\mathbf{y}_k$ is given by

$$\mathbf{y}_k = \sqrt{E_s / M}\,\mathbf{H}_k \mathbf{F}_k \mathbf{s}_k + \mathbf{n}_k \quad (1)$$

where k is the subcarrier index, E_s is the total transmit power for the k-th subcarrier, $\mathbf{H}_k$ is the $N_R \times N_T$ normalised channel matrix, $\mathbf{s}_k$ is an $M \times 1$ transmit data symbol vector (which is spread over N_T transmit antennas by multiplying by an $N_T \times M$ precoding matrix $\mathbf{F}_k$), and $\mathbf{n}_k$ is an $N_R \times 1$ noise vector whose entries are complex, independent and identically distributed (i.i.d) additive white Gaussian noise (AWGN) samples with zero mean and variance σ^2.

The received symbol vector $\mathbf{y}_k$ is decoded using an MMSE linear decoder $\mathbf{G}_k$, given by

$$\mathbf{G}_k = \left[\mathbf{F}_k^* \mathbf{H}_k^* \mathbf{H}_k \mathbf{F}_k + \left(M\sigma_n^2 / E_s\right)\mathbf{I}_M\right]^{-1} \mathbf{F}_k^* \mathbf{H}_k^* . \quad (2)$$

The optimal precoder matrix $\mathbf{F}_{opt}$ is determined for each subcarrier using the minimum mean square error (MSE) criterion [5] as

$$MSE\left(\mathbf{F}_k\right) = \frac{E_s}{M}\left(\mathbf{I}_M + \frac{E_s}{M\sigma_n^2}\mathbf{F}_k^* \mathbf{H}_k^* \mathbf{H}_k^* \mathbf{F}_k^*\right)^{-1} \quad (3)$$

where

$$\mathbf{F}_{opt} = \arg\min_{\mathbf{F}_k^i \in Q} trace\left(MSE\left(\mathbf{F}_k^i\right)\right) \quad (4)$$

and Q is the codebook (which is known to both the BS and MS). Q is constructed using the methods described in section 8.4.5.4.10.15 of [2].

B. Dominant Eigenbeamforming (DE)

The second linear precoding system considered in this paper is dominant eigenbeamforming (DE). Here the BS transmits a single spatial stream across the N_T transmit antennas.

In a precoded mobile WiMAX system, the k-th subcarrier is assigned a $N_R \times 1$ precoder vector $\mathbf{f}_k$. The receive symbol vector $\mathbf{y}_k$ for a DE system can be expressed as

$$\mathbf{y}_k = \sqrt{E_s}\,\mathbf{H}_k \mathbf{f}_k s_k + \mathbf{n}_k . \quad (5)$$

In this paper $\mathbf{y}_k$ is decoded using a traditional maximum ratio combiner $\mathbf{g}$ [6].

$$\mathbf{g}_k = \mathbf{H}_k \mathbf{f}_k / \left\|\mathbf{H}_k \mathbf{f}_k\right\|_2 . \quad (6)$$

The optimal precoder vector $\mathbf{f}_{opt}$ is determined from (7)using the criterion defined in [6].

$$\mathbf{f}_{opt} = \arg\max_{\mathbf{f}_k^i \in Q} \left\|\mathbf{H}\mathbf{f}_k^i\right\|_2^2 . \quad (7)$$

IV. MOBILE WIMAX LINEAR FEEDBACK MECHANISM

In a mobile WiMAX system, in order to implement downlink (DL) MIMO linear precoding, the BS must allocate a feedback channel in the uplink (UL) to each MS and request precoding matrix feedback information from the MS. The MS estimates the time varying channel matrix $\hat{\mathbf{H}}(t)$ from the preamble present in the current and previous downlink subframes, and then determines the optimal precoder matrix $\mathbf{F}(t)$ from $\hat{\mathbf{H}}(t)$. The precoder matrix $\mathbf{F}(t)$ is fed back to the BS in the second uplink subframe using the allocated fast feedback channel [10]. The BS then applies this precoding matrix to the data sent in the third downlink subframe, as illustrated in Fig. 2. There is a feedback delay of two frames from the time the optimal precoder matrix is estimated in the MS until the time it is actually used in the BS. With a frame duration τ=5ms, this feedback delay is 10ms [10]. It should be noted that Fig. 2 illustrates the feedback procedure using the frame structure of an FDD Mobile WiMAX system. However, this procedure also applies to a TDD system.

Due to the feedback delay, the BS applies the precoder matrix $\mathbf{F}(t)$, which is optimized for the channel $\hat{\mathbf{H}}(t)$, to the data transmitted over the actual channel $\mathbf{H}(t+2\tau)$. $\mathbf{F}(t)$ is not optimal for $\mathbf{H}(t+2\tau)$ since there is a time lag of 2τ between the channel estimate and the application of the precoder matrix. Higher MS velocities and Doppler spreads result in a greater degree of channel decorrelation for this delay, which leads to increased error between $\mathbf{F}(t)$ and the actual precoder matrix optimized for $\mathbf{H}(t+2\tau)$. Therefore, the use of $\mathbf{F}(t)$ over the channel $\mathbf{H}(t+2\tau)$ degrades to some degree the performance of the linear precoding system.

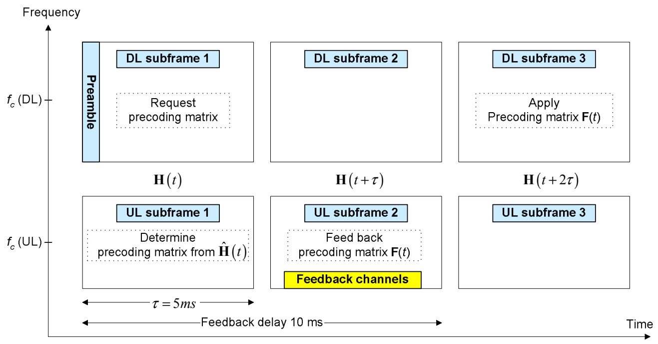

Fig. 2: Feedback delay in a FDD Mobile WiMAX system [11]

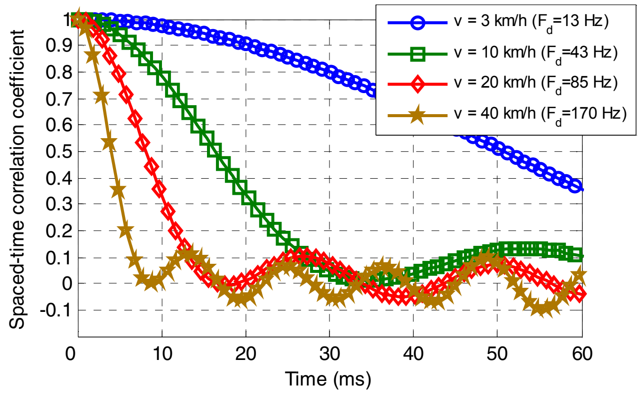

Fig. 3: Channel spaced-time correlation function for different MS velocities and Doppler spreads

Fig. 3 illustrates the channel spaced-time correlation function for the urban micro SCM [8] at different MS velocities. A carrier frequency of 2.3 GHz and a worst case Jakes' power Doppler spectrum is assumed at the MS. Fig. 3 shows the correlation coefficient between two channel realizations 10ms (or 2 frames) apart. Values of 0.98, 0.8, 0.32, and 0.01 are seen for maximum velocities of 3, 10, 20, and 40 km/h, respectively. These correspond to Doppler spreads F_d of 13, 43, 85, and 170 Hz respectively. For the Jakes spectrum F_d=2F_m, where F_m is the maximum Doppler shift given by F_m=vf_c/c. As illustrated, at speeds of 20 and 40 km/h, $\mathbf{H}(t+2\tau)$ and $\mathbf{H}(t)$ are strongly de-correlated when the Jakes Power Doppler Spectrum is assumed.

V. System Performance Analysis

This section compares the packet error rate (PER) performance of the 4×2 precoded MIMO mobile WiMAX system for different MS velocities and a 10ms feedback delay. Instead of a specific velocity, Doppler spread and delay we can also use the more generic normalised Doppler spread (F_dT), where T represents the feedback delay. A 6-bit codebook is used for the 4×2 antenna configuration [2].

A. Dominant Eigenbeamforming

As shown in [6] the performance of a DE system depends on its effective channel gain Γ, which was given by

$$\Gamma = \left\| \mathbf{Hf} \right\|_2^2 . \tag{8}$$

In the presence of a feedback delay the effective channel gain in (8) can be rewritten as

$$\Gamma(t+2\tau) = \left\| \mathbf{H}(t+2\tau)\mathbf{f}(t) \right\|_2^2 \tag{9}$$

where $\left\| . \right\|_2$ denotes the matrix two-norm.

We omit the subcarrier index k in all future equations for the purposes of simplicity.

From (9) it can be seen that as the channel $\mathbf{H}(t+2\tau)$ deviates from $\mathbf{H}(t)$ due to mobility, the effective channel gain $\Gamma(t+2\tau)$ drops from its maximum value of $\Gamma(t)$. The impact of mobility on the effective channel gain can be understood further using the graphs shown in Fig. 4, which present the cumulative distribution function (cdf) of the effective channel gain $\Gamma(t+2\tau)$ for different F_dT for a 4×2 DE system. For the parameters and channel model settings given in section II, it can be observed that at 3km/h, when the channel correlation over the feedback delay period is still very high, the effective channel gain experiences very little loss. However, as the MS velocity or Doppler spread increases, the mismatch between the channel $\mathbf{H}(t+2\tau)$ and the precoder vector $\mathbf{f}(t)$ increases, and the effective channel gain reduces. This corresponds to a significant reduction in both gain and diversity order. When the MS velocity is high (120 km/h), the channel and precoder matrix are completely mismatched. Using a strongly mismatched precoder matrix does not provide any closed-loop system benefit, and the precoding performance falls back to the 1×2 maximum ratio combining (MRC) receive diversity solution [12]. This is verified in Fig. 4, where the 4×2 DE effective channel gain cdf at 120 km/h follows closely the channel power $\sum \left| \mathbf{H}_{ij} \right|^2$ cdf of the equivalent 1×2 channel.

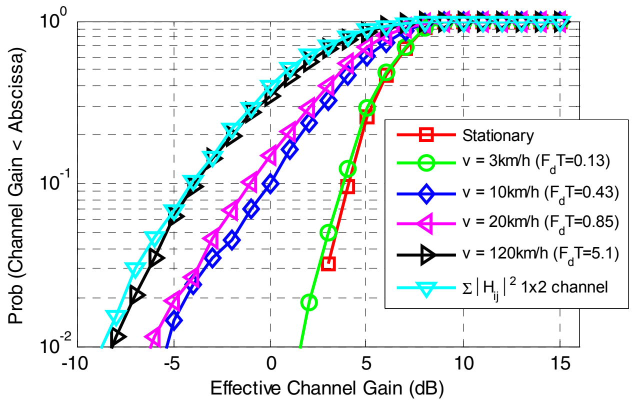

Fig. 4: CDF of 4x2 effective channel gain Γ for different velocities

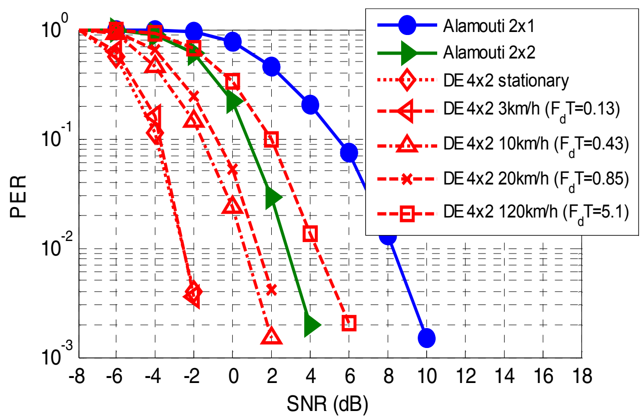

Fig. 5: PER performance of 4x2 DE QPSK 1/2 for different MS velocities, normalised Doppler spreads, and a feedback delay of 10ms

Fig. 5 illustrates the PER performance of a 4×2 QPSK 1/2 rate DE system with MS velocities of 3 km/h, 10 km/h, 20 km/h, and 120km/h. It can be seen that at an MS velocity of 3 km/h, where the channel does not change significantly during the feedback delay, the PER performance of the 4×2 DE system is close to the optimal stationary case. However, the DE performance decreases significantly when the MS velocity increases to 10 km/h and 20 km/h. More than 3dB of loss is seen at a PER of 10^{-2} and the performance approaches that of the open-loop 2×2 Alamouti system. At a velocity of 120 km/h, no precoding gain is achieved and the 4×2 DE system falls back to a 1×2 maximal ratio combining (MRC) receive diversity system. This is verified in Fig. 5, where the performance of the 4×2 DE system at 120 km/h shows approximately 3dB of array gain relative to the standard open-loop 2×1 Alamouti system. This is exactly that achieved by a 1×2 MRC system [13].

B. Linear precoding spatial multiplexing

It was shown in [5] that for a limited feedback linear precoding system using a MMSE linear receiver, its overall performance depends on the trace of the mean square error (MSE) matrix (i.e., the sum of mean squared error on each spatial stream) in (3). In the presence of feedback delay the MSE becomes

$$MSE = \frac{E_s}{M}\left(\mathbf{I}_M + \frac{E_s}{M\sigma_n^2}\mathbf{F}(t)^*\mathbf{H}(t+2\tau)^*\mathbf{H}(t+2\tau)\mathbf{F}(t)\right)^{-1} \quad (10)$$

As can be seen from (10), the more the channel matrix $\mathbf{H}(t+2\tau)$ deviates from the original channel $\mathbf{H}(t)$, the greater the MSE matrix deviates from the original MSE matrix; resulting in an increase in the *trace(MSE)*. This leads to a decrease in system performance. Fig. 6, which demonstrates the cumulative distribution function of the *trace(MSE)* for different MS velocities, clearly illustrates the inverse relationship between the magnitude of the channel-precoder matrix mismatch and the *trace(MSE)*. It can be observed that at a velocity of 3 km/h, the linear precoding SM system experiences very little increase in *trace(MSE)*. However, at velocities of 10 km/h (which maps to a normalised Doppler spread of 0.43) or higher, the *trace(MSE)* keeps increasing. At a velocity of 120 km/h the channel and precoder matrix are totally mismatched, and the *trace(MSE)* rises to the same value as that achieved by the open-loop 2×2 spatial multiplexing system. This indicates that the 4×2 linear precoding SM system falls back to the open-loop 2×2 SM system performance with a 2×2 effective channel **HF** when the incorrect precoder matrix is used.

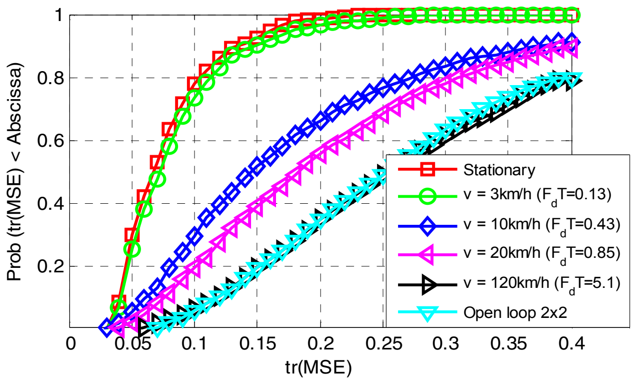

Fig. 6: CDFs of *trace(MSE)* for different MS velocities

The impact of channel-precoder matrix mismatch also reflects on the received Signal to Interference-plus-Noise Ratio (SINR) of each spatial stream, as illustrated in Fig. 7 and Fig. 8. As can be expected from the previous discussion, a higher mismatch results in a lower received SINR on both spatial streams, and at a velocity of 120 km/h, the 4×2 linear precoding SM system experiences the same received spatial stream SINR as the 2×2 open-loop SM approach.

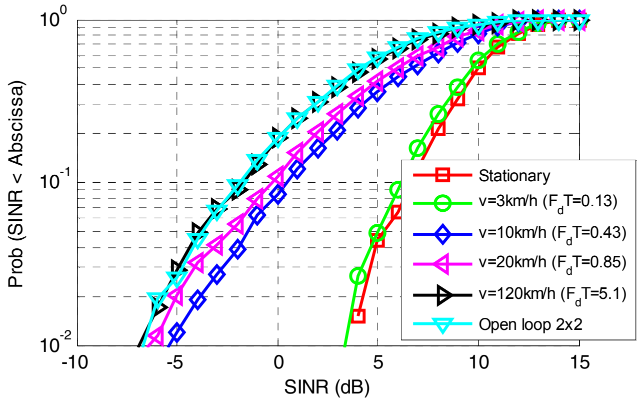

Fig. 7: CDF of received SINR on the 1st spatial stream

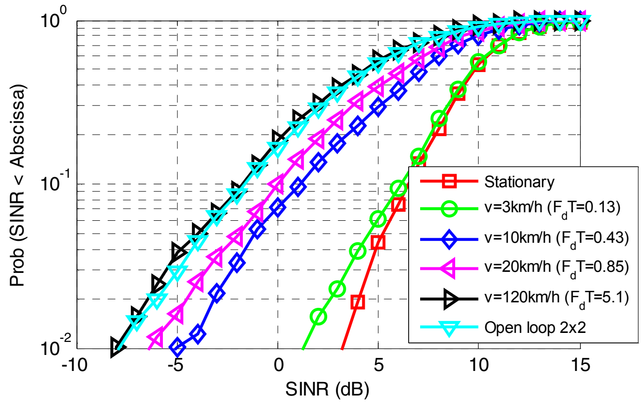

Fig. 8: CDF of received SINR on the 2nd spatial stream

The PER performance of the 4×2 1/2 rate coded QPSK linear precoding mobile WiMAX system for different vehicle speeds (and F_dT) is illustrated in Fig. 9. It can be seen that at a velocity of 3km/h, where the channel correlation for the 10ms feedback delay is still very high, the PER performance is very good (degraded by approximately 0.2dB) compared to the ideal static case. However, when the MS velocity increases to 10 and 20 km/h, the PER performance degrades dramatically to the point where it is even worse than the 4×2 open-loop SM system [14], with a significant decline in both array gain and diversity order. At a velocity of 120 km/h, channel decorrelation results in a further performance drop, with the system approaching the performance of a 2×2 open-loop SM approach. We conclude that MS mobility results in a significant reduction in the performance of a linear precoding SM system when the impact of feedback delay is included in the simulation. In particular MS velocity is limited for channels with high Doppler spread.

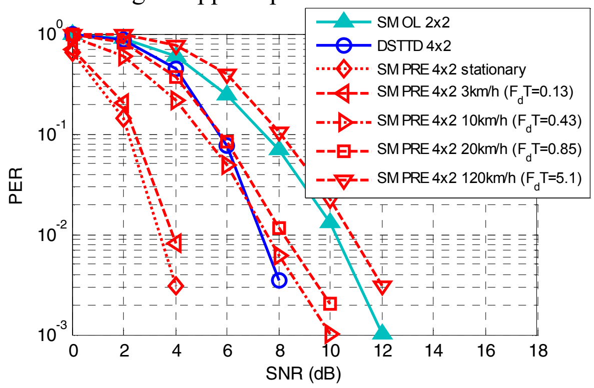

Fig. 9: PER performance of 4x2 linear precoding SM QPSK 1/2 rate system for different MS velocities and normalised Doppler spread

Table II presents the SNR loss (dB) at PER of 10^{-2} for the 4×2 DE and SM PRE systems at difference MS velocities.

TABLE II: SNR LOSS FOR DIFFERENT MS VELOCITIES

	3km/h	10km/h	20km/h	120km/h
DE 4×2	0	3	4	5.8
SM PRE 4×2	0.2	4	4.8	7.1

VI. MOBILITY MITIGATION TECHNIQUES

In order to mitigate the impact of mobility and feedback delay, and hence to support vehicular applications, two further approaches can be implemented.

A. Use of directional antennas

The error performance results presented in this paper assume that the MS employs an omni-directional antenna. Furthermore, a Jakes Power Doppler Spectrum was applied in all cases. The authors in [15] demonstrated that a mobile terminal using a directional antenna experiences a much reduced Doppler spread compared to an omni-directional antenna. With a directional antenna the mobile terminal can travel at a high velocity and still experience a similar, or even reduced, Doppler spread. The shape of the power Doppler spectrum was shown in [15] not to strongly influence the resulting error performance (assuming a constant Doppler spread). Applying these results to our PER performance in Fig. 5 and Fig. 9 implies that the precoded Mobile WiMAX performance results achieved at an F_dT of 0.13 (corresponding to v=3km/h for an omni antenna) can also be achieved at a higher velocity if the MS is equipped with an appropriate directional antenna.

It was shown in [15] that a directional antenna with a 3dB beamwidth α reduces the Doppler spread from $2F_m$ to $(1-\cos(\alpha/2))F_m$ if the antenna boresight is aligned straight ahead or behind the vehicle [16] (this assumes the vehicle moves directly forwards or backwards and that the channel experiences multipath with a uniformly distributed power azimuth spectrum). Applying a 45-degree beamwidth directional antenna at the MS, an F_dT value of 0.13 now corresponds to a velocity of 80 km/h. Directional antennas at the MS allow the vehicle to travel at significantly higher velocities while still maintaining a low normalised Doppler spread, and hence strong linear precoded performance.

B. Implementation of channel prediction

Another approach to mitigate the effect of mobility is to predict the channel response two frames (10ms) ahead, and then select the precoding matrix that is optimal for the predicted channel. Various channel prediction algorithms can be found in the literature [17].

VII. CONCLUSIONS

Results have shown that MS velocities, Doppler shift and Doppler spread all play a significant part in the performance of a linear precoding Mobile WiMAX system. Spatial Multiplexing and Dominant Eigenbeamforming systems have been studied. For a carrier frequency of 2.3 GHz and a Jakes power Doppler spectrum, velocities of 10 km/h or higher can seriously degrade the performance of the linear precoding system. The reason for this is the mismatch that occurs between the optimal precoder matrix and the actual channel over which the precoded signal is sent. At very high velocities (e.g., 120 km/h) the channel and the precoding matrix are strongly mismatched, and using the precoder in this condition for channels with high Doppler spread does not provide any benefits. Results show that the linear precoding system falls back to the open-loop system with an effective channel **HF**. Interestingly, in this case a linear precoding MIMO system with more antennas, i.e., 4×2 SM PRE and 4×2 DE PRE, experiences the same performance as an open-loop MIMO system with fewer antennas, i.e., 2×2 SM and 1×2 MRC respectively. This performance degradation indicates one important point, namely that the codebook based feedback system is very sensitive to mismatches in the precoder matrix. When the channel correlation over the feedback delay (10ms) is high (0.98 at v = 3km/h), the resulting precoder matrix is near optimal. However, when the channel correlation decreases (0.8 at v = 10 km/h), the precoder matrix is no longer optimal and the system performance drops dramatically. We conclude that when feedback delay is considered, the precoded mobile WiMAX system using omni directional antennas is only suitable for pedestrian applications. To support vehicular velocities directional antennas and/or channel prediction must be applied.

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