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A Novel Pilot Expansion Approach for MIMO Channel Estimation

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KEYWORD

MIMO
Pilot Expansion technique
Paley-Hadamard matrix
Feedback Kalman filter

ABSTRACT

A training-based MIMO channel estimation scheme is presented to operate in severe frequency and time selective fading channels. Besides the new pilot bits designed from the 'Paley-Hadamard' matrix to exploit its orthogonal and 'Toeplitz-like' structures and minimising its pilot length, a novel pilot expansion technique is proposed to estimate the length of the channel impulse response, by flexibly extending its pilot length as required in order to capture the number of multipath existed within the MIMO channel. The pilot expansion can also help to deduce the initial channel variation and its Doppler rate which can be subsequently applied for MIMO channel tracking using decision feedback Kalman filter during the data payload.

1 Introduction

The multiple-input multiple-output (MIMO) system has been recognized as one key solution for future generation fast speed communication due to its capability to exploit multipath while realizing high performance in spatial array, multiplexing and power gain [Sampath, H. et al 2002, Stuber, G.L. et al 2004, Li Y.G. et al 2002]. Particularly, this technology becomes of increasing interest to the wireless localization [Rodríguez, S. et al. 2014, Santana, J. F. et al. 2014] and multi-agent systems [Corchado, C. et al. 2010, Carrascosa, C. et al. 2008]. Merging with existing orthogonal frequency division multiplexing (OFDM) technologies, MIMO-OFDM systems can boost data transmission rate while handling frequency-selective (FS) fading However, to allow and enable high mobility practicability, such systems must also be capable to obtain accurate channel information for symbol recovery in high speed; while tackling time selective (TS) fading and co-channel interference (CCI).

In fact, various smart channel estimation (CE) [Zamiri-Jafarian H. et al 2007, Huang Q. et al 2009, Angelosante D. et al 2009, Zhong K, et al 2013, Chen Y.C. et al 2010] and channel tracking (CT) techniques [Song W.G. et al2006, Duel-Hallen A., et al 2007, Komninakis C. et al 2002] have been proposed to provide estimates on the channel impulse response (CIR) or channel frequency response (CFR). Many researches focus on efficient pilot design and allocation methods [Barhumi I. et al 2003, Wang X. et al 2005, Biguesh M. et al 2006, Bogale, T.E. et al. 2014, MA, J. et al. 2011, Manasseh, E. et al. 2013] for separate FS and TS cases where [Biguesh M. et al 2006] gives a solid overview on pilot requirements. In general, the trend of assuming or relying on the prior knowledge of a) the length of CIR and b) Doppler rate, frequently become the bottleneck to perform well in real TS and FS fading channels. Many complex methods build on tedious approximation and rely sufficiently high-order polynomial model, rendering impractical solution for real time CE where the optimality of the pilot ultimately depends on the speed of CE. In this paper, TS and FS fading channels have been assumed and simulated using the Jakes and Bello models [Dent, P. et al. 2006, Bello, T, 1963]. Both MIMO-CE and CT schemes have been devised to realise practical communications in both FS and TS channels.

First, pilot bits are carefully de-signed to shorten the length of the training period via a unique combination of the 'orthogonal' and 'Toeplitz-like' structure ascertained from the integrated Paley-Hadamard (P-H) matrix [Siyau, M.F. et al. 2003] (extension to a fractionally-sampled case can be found in [Siyau, M.F. et al. 2004]), in order to resolve both CCI and inter-symbol interference (ISI) while estimating individual CIR on each transmit (Tx) and receive (Rx) antenna pairs.

The novelty of this paper is the next 'Pilot Expansion' (PE) technique which has the capability to further exploit the P-H code structure and to flexibly extend the pilot length as required, in order to a) approximate the length of CIR, L and b) reveal the time-variation information of the respective TS channels. The proposed PE technique is also crucial for the subsequent provision of channel tracking for individual CIR or CFR to ensure receiver's resiliency against severe TS fading environment and achieve accurate receiver's setting during the symbol recovery and decision feedback process. Here, the MIMO-OFDM system is chosen to showcase the proposed CE, PE and CT methods, although their extensions to any future MIMO- systems can also be realisable.

The remainder of this paper is organized as follows. Section 2 describes the basic channel model. Section 3 presents the MIMO-CE and a novel pilot expansion technique. Kalman-CT is presented in section 4. The simulation results and discussion are shown in section 5. Finally, section 6 concludes the paper.

2 MIMO Channel Model

The time domain (TD) time-varying sampled CIR from i^{th}-*Tx* antenna to j^{th}-*Rx* antenna can be termed as:

$$\mathbf{h}_{ji}(t) = \left[h_{ji}(0,t) \quad h_{ji}(1,t) \quad \dots \quad h_{ji}(L-1,t) \right]^{\mathrm{T}} \qquad (1)$$

where L is number of multipath on each *Tx-Rx* antenna pair. $h_{ji}(l,t)$ is the individual TD channel coefficient on l^{th} path at time t. The MIMO channel will be formed by $\mathbf{h}_{ji}(t)$ shown in (4) later. The corresponding time-varying sampled CFR from i^{th} *Tx* to j^{th} *Rx* antenna can be found by applying the inverse fast-Fourier transform (*ifft*) function to $\mathbf{h}_{ji}(t)$ in (1) as:

$$\mathbf{g}_{ji}(t) = ifft\left(\mathbf{h}_{ji}(t), N\right) = \left[g_{ji}(0,t) \quad g_{ji}(1,t) \quad \dots \quad g_{ji}(N-1,t) \right]^{\mathrm{T}} (2)$$

where N is the number of *ifft* point $g_{ji}(n,t)$ is the individual frequency domain (FD) channel coefficient on n^{th} subcarrier at time t. The time-correlation between the adjacent TD coefficients is governed by the Doppler rate f_DT, (f_D is the maximum Doppler frequency and T is the baud duration) as:

$$E\left\{ h_{ji}(t_1)\, h_{ji}^{*}(t_2) \right\} \approx J_0\left(2\pi f_D T \left| t_1 - t_2 \right| \right) \qquad (3)$$

where $J_0(\cdot)$ is the zero-order Bessel function of the first kind. Thus, the resultant $g_{ji}(n,t)$ in (2) must have the same time-varying property with the similar Doppler rate and the time-correlation between the adjacent FD coefficients as $h_{ji}(l,t)$. Note that $(.)^{\mathrm{T}}$ is denoted for the transpose

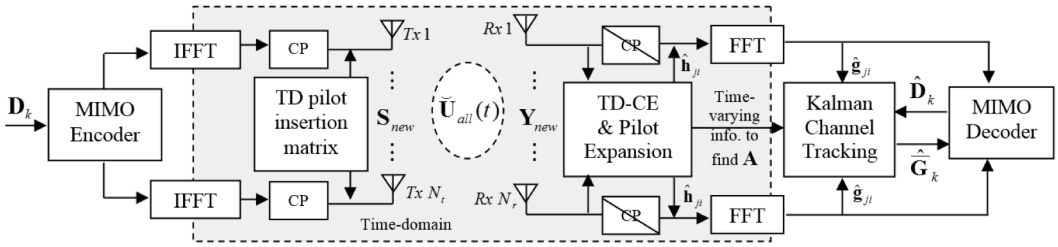

Fig.1 Proposed Channel Estimation with novel Pilot Expansion Scheme and Kalman Channel Tracking

operation and $(.)^{H}$ is denoted for the Hermitian operation.

3 MIMO Channel Model

A MIMO-CE scheme in Fig.1 is proposed to concurrently estimate corresponding CIRs and its 'L' length while revealing the channel variation information via a novel pilot expansion (PE) technique utilizing flexible PE models shown in (12) and (13) later that 'encompass' the FS MIMO channel for TS case.

3.1 MIMO-CE Utilizing P-H Codes

To provide a virtual 'division' on individual CIR in FS case, each basic channel matrix consisting of all CIRs, $\mathbf{h}_{ji}(t)$, *with respect to (w.r.t)* each *Tx* antenna can be written as:

$$\mathbf{U}_i(t) = \begin{bmatrix} \mathbf{h}_{1i}^{\mathsf{T}}(t) \\ \vdots \\ \mathbf{h}_{N_r i}^{\mathsf{T}}(t) \end{bmatrix} = \begin{bmatrix} h_{1i}(0,t) & \cdots & h_{1i}(L-1,t) \\ \vdots & \ddots & \vdots \\ h_{N_r i}(0,t) & \cdots & h_{N_r i}(L-1,t) \end{bmatrix} \quad (4)$$

where 'i' = 1 to N_t and L multipath exists in each CIR. Next, to facilitate an efficient MIMO-CE, all $\mathbf{U}_i(t)$ (i = 1, …, N_t) can be concatenated to form the complete MIMO channel as:

$$\mathbf{U}_{all}(t) = \begin{bmatrix} \mathbf{U}_1(t) & \cdots & \mathbf{U}_{N_t}(t) \end{bmatrix} \quad (5)$$

The time-index 't' is temporarily changed to 'n' in order to differentiate the 'virtual variation' due to 'n' sequence of pilot bits as oppose to the actual variation in time. Thus, TD signal interactions at n^{th} sample at the receiver can be viewed as:

$$\mathbf{y}(n) = \mathbf{U}_{all}(n)\,\Im(n) = \begin{bmatrix} y_1(n) \cdots y_{N_r}(n) \end{bmatrix}^{\mathsf{T}} \quad (6)$$

$$\Im(n) = \begin{bmatrix} \mathbf{s}_1(n) & \cdots & \mathbf{s}_{N_t}(n) \end{bmatrix}^{\mathsf{T}} \quad (7)$$

$$\mathbf{s}_i(n) = \begin{bmatrix} s_i(n) & s_i(n-1) & \cdots & s_i(n-L+1) \end{bmatrix}^{\mathsf{T}} \quad (8)$$

Note that $\Im(n)$ consists of N_t number of *Tx* vector, $\mathbf{s}_i(n)$, sent by individual i^{th} *Tx* antenna. Each $\mathbf{s}_i(n)$ contains L length of *Tx* pilot bits; from current n^{th} bit to past $(n\text{-}L\text{+}1)^{\text{th}}$ bit, which convolve with different coefficients $h_{ji}(n,t)$.

The aim is to design pilot codes in $\mathbf{s}_i(n)$ such that pilot vectors $\Im(n)$ can differentiate individual *Tx* antenna for virtual segregation of all its CIRs. The pilot matrix, $\mathbf{S}_{pilot}$ can be formed as:

$$\mathbf{S}_{pilot} = \begin{bmatrix} \Im(n) & \Im(n+1) & \cdots & \Im(n+v-1) \end{bmatrix} \quad (9)$$

where 'v' is the chosen matrix order. Each row sequence in $\mathbf{S}_{pilot}$ is designed to be orthogonal *w.r.t* other row sequences. Next, the CE can be performed with 'L' known *a priory* as:

$$\hat{\mathbf{U}}_{all} = \mathbf{Y}\ \mathbf{S}_{pilot}^{\mathsf{H}} \quad (10)$$

where $\mathbf{Y}$ is the corresponding *Rx* pilot matrix with the proper samples collection of $\boldsymbol{y}(n)$ at every 'L' intervals as:

$$\mathbf{Y} = \begin{bmatrix} \mathbf{y}(n) & \mathbf{y}(n+L) & \cdots & \mathbf{y}(n+(v-1)L) \end{bmatrix} \quad (11)$$

The challenge is to design $\mathbf{S}_{pilot}$ such that the gap between the collection intervals of $\boldsymbol{y}(n)$ in $\mathbf{Y}$ can be further reduced to include adjacent samples, while ensuring the CE accuracy in (10). This can be achieved by utilizing the P-H matrix codes which provides both orthogonal and 'Toeplitz-like' unique combined structure. An example of pilot matrix with the P-H codes for $v = 8$, $N_t = 2$ $L \leq 4$ is shown below:

$$\mathbf{S}_{pilot} = \begin{bmatrix} +s & +s & +s & +s & +s & +s & +s \\ -s & -s & -s & +s & -s & +s & +s \\ +s & -s & -s & -s & +s & -s & +s \\ +s & +s & -s & -s & -s & +s & -s \\ -s & +s & +s & -s & -s & -s & +s \\ +s & -s & +s & +s & -s & -s & -s \\ -s & +s & -s & +s & +s & -s & -s \\ -s & -s & +s & -s & +s & +s & -s \end{bmatrix} \begin{matrix} \\ \\ \\ \\ \\ \\ \\ \\ \end{matrix} \begin{matrix} \\ \\ \\ \\ Tx\text{-}1 \\ \\ \\ \\ \end{matrix} \begin{matrix} \\ \\ \\ \\ \\ \\ \\ Tx\text{-}2 \end{matrix}$$

$$\mathbf{S}_{pilot} = \begin{bmatrix} \Im(n) & \Im(n+1) & \cdots & \cdots & \cdots & \Im(n+v-1) \end{bmatrix}$$

A thorough 'run-through' from (4) to (11), reveals that the diagonally Toeplitz-like structure can be exploited such that only v+2(L–1) number of pilot bits (instead of vL) are required per *Tx* antenna, as shown in the colored regions. Pilot bits in those non-colored regions can avoid to be sent, while retaining the same $\mathbf{S}_{pilot}$ formation at the receiver for CE in (10). This allows almost every successive samples of $\boldsymbol{y}(n)$ to be utilized instantly without gap,

instead of waiting every '*L*' interval as in (11), thereby further shortening the pilot length and overall CE processing time that is crucial in the TS channels case.

3.2 Novel Pilot Expansion (PE) Technique

Next, the MIMO-CE scheme is further developed to a) estimate the length of CIRs and b) reveal channel variation. In reality, length '*L*' in each CIR is unknown, while the ultimate size of $\hat{\mathbf{U}}_{all}$ in (10) depends solely on the amount of samples collection $\boldsymbol{y}(n)$ in $\mathbf{Y}$ and corresponding $\mathbf{S}_{pilot}$ formation at the receiver. Thus, it is vital to allow flexible extension in pilot length to cater every possible '*L*' while keeping the MIMO-CE process intact. To effectively 'capture' this information, an approximation PE model of $\mathbf{U}_i(t)$ in (4) can be formed as:

$$\breve{\mathbf{U}}_i(t) = \begin{bmatrix} \breve{\mathbf{h}}_{1i}^{\mathsf{T}}(t) \\ \vdots \\ \breve{\mathbf{h}}_{N_r i}^{\mathsf{T}}(t) \end{bmatrix} = \begin{bmatrix} \breve{h}_{1i}(0,t) & \cdots & \breve{h}_{1i}(L_{est}-1,t) \\ \vdots & \ddots & \vdots \\ \breve{h}_{N_r i}(0,t) & \cdots & \breve{h}_{N_r i}(L_{est}-1,t) \end{bmatrix} \tag{12}$$

where L_{est} is the 'guess' length of CIR and $L_{est} \geq L$ so that estimated $\breve{\mathbf{U}}_i(t)$ in (12) is always wider than $\mathbf{U}_i(t)$ in (4). Intuitively, sending a longer pilot sequence of pilot vectors will ensure that the estimate of $\breve{\mathbf{h}}_{ji}^{\mathsf{T}}(t)$ is always sufficient to approximate the actual $\mathbf{h}_{ji}(t)$, with additional (L_{est}–L) CIR 'residues' at the tail of $\breve{\mathbf{h}}_{ji}^{\mathsf{T}}(t)$ estimate. These residues are usually near 'zero' value, which can be removed (or further utilized). However, using only a single $\breve{\mathbf{U}}_i(t)$ PE model in (12) can render insufficient CE accuracy in the high noise case. Thus, to guarantee a better expectation of CE, a further extended approximation PE model on $\mathbf{U}_{all}(t)$ is required as:

$$\breve{\mathbf{U}}_{all}(t) = \begin{bmatrix} \breve{\mathbf{U}}_1(t) & \cdots & \breve{\mathbf{U}}_{N_t}(t) & 0 & \cdots & 0 \\ & \ddots & & & \ddots & \\ 0 \cdots 0 & & \mathbf{U}_1(t+M) & \cdots & \mathbf{U}_{N_t}(t+M) & \end{bmatrix} \tag{13}$$

where $\breve{\mathbf{U}}_{all}(t)$ contains (M+1) blocks of $\breve{\mathbf{U}}_i(t)$ in succession which implies they can now be jointly evaluated to increase the CE accuracy. For a time-invariant channel, all $\breve{\mathbf{U}}_i(t)$ to $\breve{\mathbf{U}}_i(t+M)$ will be quite similar, thus, render a positive estimation of $\breve{\mathbf{U}}_i(t)$. When the channel is time-varying, changes in CIRs are also gradually revealed across from all $\breve{\mathbf{U}}_i(t)$ to $\breve{\mathbf{U}}_i(t+M)$, providing the vital clue to unveil the time-variation information (i.e. the Doppler rates and travel velocities) while the basic CE is carried out. In fact, L_{est} can initially take a larger value to include M in order to estimate $\breve{\mathbf{U}}_i(t)$ and the length of CIR in (12) first (as the resultant residues will implicate the actual CIR length) and then adapt M as (L_{est}–L) to further process $\breve{\mathbf{U}}_{all}(t)$ in (13).

To achieve this, $\mathbf{S}_{pilot}$ in (9) must be capable to be flexibly expanded to satisfy the formation of $\breve{\mathbf{U}}_{all}(t)$ in (13), while keeping pilot length to minimum requirement and resolving CCI, FS and TS channels concurrently for a large MIMO channel during CE, which is the key highlight in the PE technique. To show this, pilot bits in $\mathbf{s}_i(n)$ in (8) are extended to include (M+L_{est}–L) additional bit per *Tx* antenna as:

$$\breve{\mathbf{s}}_i(n) = \left[s_i(n) \;\; s_i(n-1) \;\; \cdots \;\; s_i(n-L_{est}-M-1) \right]^{\mathsf{T}} \tag{14}$$

This will render a corresponding $\Im_{new}(n)$ and $\mathbf{B}(n)$ as:

$$\mathbf{B}(n) = \breve{\mathbf{U}}_{all}(n)\, \Im_{new}(n) = \left[\mathbf{y}(n+M) \cdots \mathbf{y}(n) \right]^{\mathsf{T}} \tag{15}$$

where $\mathbf{B}(n)$ now contains several basic vector $\boldsymbol{y}(n)$ in (6) in succession. $\Im_{new}(n)$ can still be formulated using (7) with $\breve{\mathbf{s}}_i(n)$ in (14) replacing $\mathbf{s}_i(n)$ in (8). Thus, the new pilot matrix $\mathbf{S}_{new}$ expanded from (9) with a new Hadamard order-v:

$$v > N_t \times (L_{est} + M) \tag{16}$$

Hence, the new CE with pilot expansion requires total pilot bits of v+2(L_{est}+M–1) per *Tx* antenna and is performed as:

$$\hat{\breve{\mathbf{U}}}_{all} = \mathbf{Y}_{new}\, \mathbf{S}_{new}^{\mathsf{H}} \tag{17}$$

where $\mathbf{Y}_{new}$ is the corresponding new *Rx* pilot matrix with the proper blocks collection of $\mathbf{B}(n)$ from (15) as:

$$\mathbf{Y}_{new} = \left[\mathbf{B}(n) \;\; \mathbf{B}(n+1) \cdots \mathbf{B}(n+v-2) \;\; \mathbf{B}(n+v+L_{est}+M-1) \right] \tag{18}$$

Note that there is a short waiting gap between the last two blocks $\mathbf{B}(n+v-2)$ and

$\mathbf{B}(n+v+L_{est}+M-1)$ in order to obey the crucial P-H formation in $\mathbf{S}_{new}$ needed in (17). Once $\widehat{\breve{\mathbf{U}}_{all}}(t)$ is obtained, each $\breve{\mathbf{U}}_i(t)$ within can be jointly evaluated for the channel time-variation information and its 'L' length in CIRs.

4 Kalman Channel Tracking

To compliment the proposed PE method in TS channel case, the Kalman approach [Komninakis, C. et al. 2002] is used for channel tracking. TD $\hat{\mathbf{h}}_{ji}(t)$ are changed into FD $\hat{\mathbf{g}}_{ji}(t)$ and re-arranged as $\bar{\mathbf{G}}_k$, and tracked subsequently by the Kalman algorithm below:

Step 1. Projection/Update Equations

$$\hat{\bar{\mathbf{G}}}_{k+1}^{-\,\mathsf{T}} = \mathbf{A}\,\hat{\bar{\mathbf{G}}}_{k}^{\,\mathsf{T}} \tag{19}$$

$$\mathbf{P}_{k+1}^{-\,\mathsf{T}} = \mathbf{A}\,\mathbf{P}_k\,\mathbf{A}^{\mathsf{T}} + Q \tag{20}$$

Step 2. Measurement Equations

$$\mathbf{K}_k = \mathbf{P}_k^{-}\,(\hat{\mathbf{D}}_k^{\mathsf{T}})^{\mathsf{H}}\left(\hat{\mathbf{D}}_k^{\mathsf{T}}\,\mathbf{P}_k^{-}\,(\hat{\mathbf{D}}_k^{\mathsf{T}})^{\mathsf{H}} + \sigma^2\right)^{-1} \tag{21}$$

$$\hat{\bar{\mathbf{G}}}_k^{\,\mathsf{T}} = \hat{\bar{\mathbf{G}}}_k^{-\mathsf{T}} + \mathbf{K}_k\left(\mathbf{X}_k^{\mathsf{T}} - \hat{\mathbf{D}}_k^{\mathsf{T}}\,\hat{\bar{\mathbf{G}}}_k^{-\mathsf{T}}\right) \tag{22}$$

$$\mathbf{P}_k = \left(\mathbf{I}_{N_t N} - \mathbf{K}_k\,\hat{\mathbf{D}}_k^{\mathsf{T}}\right)\mathbf{P}_k^{-} \tag{23}$$

where $\mathbf{K}_k$ is the Kalman gain. $\mathbf{P}_k$and $\mathbf{P}_k^{-}$ are the posterior and prior estimate error covariance matrices, $\mathbf{I}_{N_tN}$is the N_tN -size identity matrix, Q and $\sigma^2$are noise covariance for the process and measurement models. $\mathbf{A}$ is the update matrix. All initialization parameters above are properly tuned to yield a good CT mechanism, refer to [Komninakis, C. et al. 2002] therein for further insight.

As mentioned in (3), the FD coefficients in CFRs have the same time-variation property as the TD channel coefficients in CIRs, where the time-correlation between the adjacent samples follow similar Doppler rate, f_dT in Bello model [Bello, T, 1963]. Hence, it is vital to reflect this information in $\mathbf{A}$ in order to track ahead the estimates accurately. The estimate of $\breve{\mathbf{U}}_{all}(t)$ offers some vital clues as the displacements of coefficients from $\breve{\mathbf{U}}_i(t)$ to $\breve{\mathbf{U}}_i(t+M)$ in (13) and can be used to predict the corresponding mobile velocity, $\hat{\mu}$ and the Doppler shift frequency, $\hat{f}_d$ (from the known Tx bit rate, T). With these estimates, the variation pattern of each coefficient in CFR can be approximated: First, forming a virtual waveform as: $\cos(2\pi\hat{f}_dT + \theta_{ji}(l)$ with the phasor $\theta_{ji}(l)$ defined for each 'l' path from i^{th} Tx to j^{th} Rx antenna. Next, taking the difference between every adjacent sample-pair and normalize them. The result offers a weighted projection 'gradient' with the variant rate similar to (3) and can be combined with the actual variation magnitude of each CFR coefficient that has already been revealed in the changes from $\breve{\mathbf{U}}_i(t)$ to $\breve{\mathbf{U}}_i(t+M)$ in (13) for time variation on the channels.

5 Results and Discussions

The preliminary results of the proposed MIMO-CE with the novel pilot expansion (PE) technique are studied using the parameters set in Table 1 below and the mean Frobenius norm squared error (MSE) of the channel estimates as compared to the original channels. For consistency, the MSEs are taken at the mid-length of the total pilot bits sent per each Tx antenna. The QPSK modulation scheme is used throughout the simulation model.

Table 1. Parameters for Simulation

Symbol	Parameter	Value
f_c	Carrier frequency	2.1 GHz
R	Data rate per Tx	600kbps
μ	Vehicle mobile velocity	55km/hr, 115km/hr
L	Length of CIR	3 (equally spaced by one sample)
N	FFT/IFFT size	512
C	Frame length	200 OFDM symbols
$N_r \times N_t$	MIMO configuration	(3 ✕ 2) : 2 Tx & 3 Rx antenna

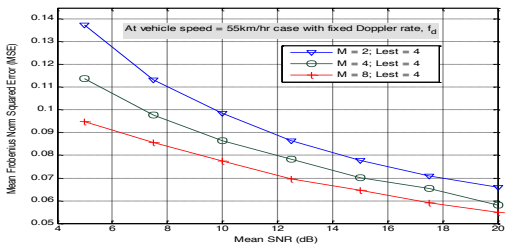

Fig.2. The performance of PE with different M, for 55km/hr channel.

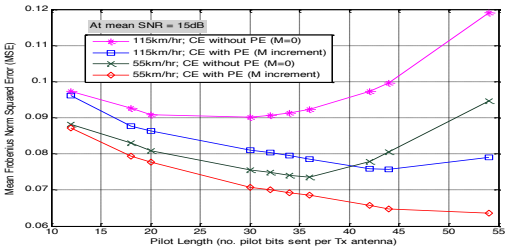

Fig.3. Impact of CE with/without PE for μ=55km/hr & 115km/hr channels.

Fig. 2 shows the impact of the chosen '*M*' values of the PE technique on the estimation accuracy at different mean SNRs for a μ = 55km/hr channel where the MSE improves as '*M*' increases for better averaging of channel estimates. The results suggested that using '*M*' blocks of $\tilde{\mathbf{U}}_i(t)$ for joint evaluation, can help to further improve the channel estimates. However, as shown in Fig.3 later as '*M*' becomes higher, the MSEs tends to depreciate due to the variation of the channel interaction with individual pilot bits. Fig. 3 compares the case using two channel velocities at SNR=15dB and shows the impact of having PE technique as the pilot length increases. For (*M*=0) case, where pilot length is allowed to increase without the help of PE, the result seems to suggest there is an optimal pilot length for different channel speed that limits the estimates to be further improved. With the use of PE (*M* increment), the CE can cope better with the channel variations as MSEs have been improved as compared to the case without the use of PE technique. Fig.3 is based on L_{est}= *L* =3. For CE with the PE assistance, the total pilot length: $v+2(L_{est}+M-1)$ required per *Tx* antenna (as the valid matrix order-*v* in (16) and block '*M*' of PE increases) can be shown below:

'*M*' block of pilot expansion	0	2	4	6	8	10
Pilot matrix order '*v*'	8	12	20	20	24	32
Pilot bits sent per *Tx* antenna	12	20	32	36	44	56

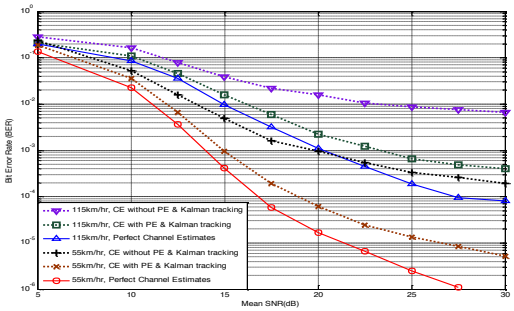

Fig. 4. The BER performance of (3×2) MIMO-OFDM system with μ=55 km/hr & 115 km/hr, and *R* = 600kbps/*Tx*.

Next, the behavior of the CE and CT is jointly studied where CE pilot training is carried out for every data frame followed by the Kalman-CT for each OFDM symbol delivery within the frame. The bit error rate (BER) system performance of a (3×2) MIMO-OFDM system under both TS and FS fading channels is shown in Fig.4. The results are plotted for two mobile velocities for three different conditions: a) perfect CE, b) CE with PE & Kalman-CT and c) CE without PE & Kalman-CT. The preliminary results show the potential of the proposed CE-PE and Kalman-CT features in achieving a better symbol recovery and BER when utilized together.

6 Conclusions

A novel MIMO channel estimator with the proposed Pilot Expansion technique has been implemented for MIMO-based systems that operate in both frequency and time selective fading channel. The advantage of having the PE technique has been shown in the preliminary results where the new jointly CE-PE scheme can effectively predict the length of CIR and channel time-variation as well as carried out more robust channel estimation for MIMO systems. The Kalman channel tracking with decision feedback algorithm has also been incorporated to assist the CE-PE process and cater for TS channels case. The performance of the joint CE & CT has been carried out and it is found that the proposed method is capable to provide effective MIMO channel estimation with potential tracking provision. The proposed PE methods yield a positive BER performance

that is closed to the results when perfect channel estimates and linear tracking are assumed.
Nonetheless, the work is at preliminary stage where its intention is only to demonstrate the idea and usefulness of the proposed Pilot Expansion technique. More investigation will be conducted to test and analyse the predictability of the Doppler information of the FS and TS channels using both proposed CE-PE and Kalman tracking combination. Future research can include the complexity analysis and further investigation on both linear and non-linear Doppler variation with different lengths of CIR on the proposed MIMO channel estimator with different P-H codes combination.

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