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Simplified Channel Tracking for Single and Multicarrier VBLAST

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***Abstract*—VBLAST systems require accurate channel state information (CSI) to decode the received signal. Such knowledge is usually obtained via a training sequence. However; in fast fading channels, the channel coherence time is very small due to the high Doppler shift, therefore the channel estimate from the training becomes inaccurate as the decoding proceeds. Sending the training sequence more frequently improves the performance at the cost of increased overhead. In this paper we introduce a novel channel tracking algorithm for single and multicarrier VBLAST in vehicular networks that does not require any change in the overhead. The algorithm uses simplified Kalman filters therefore it has low complexity. The algorithm also reduces the effects of inter-carrier-interference (ICI) in OFDM systems. Simulation results showed improvement in mean square error (MSE) and BER when using this algorithm compared to the traditional training based method.**

***Keywords*—Channel Estimation, MIMO, VANET, VBLAST.**

I. INTRODUCTION

The capacity of multiple input multiple output (MIMO) systems was shown to increase with the number of antennas [1]. Several algorithms to achieve part of this capacity have been developed, including space time block codes (STBC), space time trellis codes (STTC) and Bell Labs lAyered Space Time (BLAST) algorithms. Space Time codes increase the reliability of the link thus making it possible to use high order modulations to achieve higher data rates. BLAST systems, on the other hand, assume the receiver antennas are in a rich Rayleigh fading environment causing each antenna to receive an independent signal.

Vertical-BLAST (VBLAST) makes use of the channel state matrix (**H**) to decode the signal recursively. It starts decoding with the signal that has the highest SNR then cancels its contribution (interference) in the received signal vector. Other BLAST algorithms exist such as Diagonal, Horizontal and Turbo BLAST but they require more complicated transmitters and/or receivers than VBLAST [2-4].

In VANET vehicles communicate in an ad hoc mode while moving at high speeds, therefore relative speeds of 200km/hr or more between cars in opposite directions are not uncommon.

The frequency band allocated for VANET networks is at 5.9GHz leading to a Doppler shift of 1100Hz for 200 km/hr speed, and a channel coherence time of approximately 162μs [5]. When using a training sequence for channel estimation, the short coherence time means a small number of symbols can be transmitted between two training periods thus reducing the bandwidth efficiency due to the large overhead. This is particularly important in VANET since the communication time between the vehicles is very short therefore high data rates are essential to exchange as much information as possible during this small time. To achieve these rates, VBLAST-OFDM systems can be used since they have high spectral efficiency. However, most of the current research focuses on fixed or slowly varying links, employed in personal mobile communications, where a training sequence is sufficient to estimate the CSI. Moreover, as the speed increases, the subcarriers in OFDM spread due to the Doppler shift leading to Inter Carrier Interference (ICI) [6].

In this paper we analyse and extend the algorithm introduced in [7] for updating the channel estimate in a flat fading channel to OFDM systems. We assume an initial estimate of the channel is available, possibly from a training sequence, and the algorithm enhances this estimate so that longer packets and/or better BER can be achieved. The algorithm can work with any MIMO system but, when combined with VBLAST, can be implemented with a minor increase in hardware complexity. We assume flat fading with known maximum Doppler shift and signal to noise ratio. The algorithm is analysed via Monte Carlo simulations.

The rest of the paper is organised as follows: section II presents some related work. Section III is the mathematical derivation of the channel update algorithm. Section IV describes the simulations and the results obtained. Finally, section V summarizes the main contributions of this work.

II. RELATED WORK

Channel estimation has been of interest for many research works. In [8-10] the optimum training sequence for MIMO systems has been investigated. It was shown in [8] that an orthonormal training set is the optimum training sequence for MIMO channels.

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These can be used to obtain an initial estimate of the channel. In [11] the authors considered the use of Kalman filtering to track the channel for orthogonal STBC MIMO. They exploited the orthogonality of the codes to reduce the complexity of the filter. BLAST signals are not necessary orthogonal, hence the algorithm cannot be applied to BLAST systems. In [12] a maximum likelihood channel tracking algorithm has been proposed. The authors modelled the channel as an auto regressive (AR) process using Clarke's power spectral density. A combination of Kalman filter and minimum mean square error decision feedback equaliser (MMSE-DFE) was used in [13] to estimate the channel. The DFE is used to estimate the transmitted signal and its output is fed to the Kalman filter for channel estimation. A polynomial fitting is then used to further enhance the channel prediction. In [14] an autoregressive moving average (ARMA) filter was used to model the channel response based on Clarke's channel power spectral density, this was then used to design a Kalman filter for tracking. These algorithms are generally complicated since they use high order filters. In this paper we use a bank of first order Kalman filters for channel updating, thus avoiding the computation complexity encountered in these algorithms. The proposed algorithm then recursively estimates the change in the channel and updates the channel matrix to minimise the estimate error, thus improving the BER performance.

Numerous papers investigated the ICI problem which occurs in OFDM systems due to high Doppler shifts. The ICI was analysed for single [6, 15] and multi antenna systems [16, 17]. Algorithms to reduce the effects of ICI we introduced in [17-21]. These algorithms either require sending extra training signals, transmitting redundant data on some subcarriers, or have high complexity.

III. Derivation Of The Channel Update Algorithm

In this section we review and extend the algorithm developed in [7] For a $p\times q$ VBLAST with p transmit and q receive antennas in a flat fading channel, the q elements column vector ($\mathbf{r}_{n-1}$) of received signals at time index n-1 can be written as [22]:

$$\mathbf{r}_{n-1} = \mathbf{H}_{n-1}\mathbf{s}_{n-1} + \mathbf{m}_{n-1} \qquad (3)$$

Here $\mathbf{H}_{n-1}$ is the $q\times p$ channel matrix, $\mathbf{s}_{n-1}$ is the p column vector of transmitted symbols and $\mathbf{m}_{n-1}$ is the q column vector of white noise at time n-1. Throughout this paper, lower and upper case bold characters represent vectors and matrices respectively while lower case characters represent elements within the matrix/vector while $(.)^{+}$ represents the Moore-Penrose pseudo inverse process.

Let the estimated channel matrix be $\hat{\mathbf{H}}_{n-1}$. The simplest BLAST receiver (zero forcing receiver) calculates an estimate of the transmitted symbols ($\hat{\mathbf{s}}_{n-1}$) using the pseudo inverse of the channel matrix ($\hat{\mathbf{H}}_{n-1}^{+}$) as:

$$\hat{\mathbf{s}}_{n-1} = \hat{\mathbf{H}}_{n-1}^{+} \times \mathbf{r}_{n-1} \qquad (4)$$

since for a full rank $q\times p$, $p\leq q$, matrix $\mathbf{H}$ we have [23]:

$$\mathbf{H}^{+}\mathbf{H} = \mathbf{I}_{\mathbf{p}} \qquad (5)$$

$\mathbf{I}_{\mathbf{p}}$ is the $p\times p$ identity matrix. Define $\Delta\mathbf{H}_n$ as:

$$\Delta\mathbf{H}_n = \left(\mathbf{r}_{n-1} - \hat{\mathbf{H}}_{n-1}\hat{\mathbf{s}}_{n-1}\right)\times\hat{\mathbf{s}}_{n-1}^{+} \qquad (6)$$

Substituting equation (3) in (6) and assuming correct decoding ($\mathbf{s}_{n-1} = \hat{\mathbf{s}}_{n-1}$) we find:

$$\Delta\mathbf{H}_n = \left(\mathbf{H}_{n-1} - \hat{\mathbf{H}}_{n-1}\right)\times\mathbf{s}_{n-1}\mathbf{s}_{n-1}^{+} + \mathbf{m}_{n-1}\mathbf{s}_{n-1}^{+} \quad (7)$$

Note that the term $\left(\mathbf{r}_{n-1} - \hat{\mathbf{H}}_{n-1}\hat{\mathbf{s}}_{n-1}\right)$ is calculated in the cancellation step of the VBLAST decoding algorithm. $\Delta\mathbf{H}_n$ can be used with a simple first order Kalman filter to improve the channel estimation as:

$$\hat{\mathbf{H}}_n = \hat{\mathbf{H}}_{n-1} + \mathbf{K}.\Delta\mathbf{H}_n \qquad (8)$$

Where $\mathbf{K}$ is a matrix of update parameters and the dot in (8) represents element by element multiplication.

We now need to find the optimum value of $\mathbf{K}$. However since the receive antennas in VBLAST should not be correlated; we need to optimise for only one antenna. Equation (7) can be rewritten for the elements of the matrix $\Delta\mathbf{H}_n$ as:

$$\Delta h_{ij}^{\ n} = \left(r_i^{\ n-1} - \sum_{l=1}^{p}\hat{h}_{il}^{\ n-1}.\hat{s}_l^{\ n-1}\right)a_j^{\ n-1} \qquad (9)$$

The lower case character represents elements of the matrix/vector denoted by upper/lower case bold character. The subscripts identify the row (i) and column (j or l) which represent receive and transmit antennas respectively while the superscript (n) denotes the time index. a_j represents the element at column j of the row vector ($\hat{\mathbf{s}}^{+}$). Equation (9) can be expanded using (3) as:

$$\Delta h_{ij}^{\ n} = \left(\sum_{l=1}^{p}\left(h_{il}^{\ n-1}.s_l^{\ n-1} - \hat{h}_{il}^{\ n-1}.\hat{s}_l^{\ n-1} + m_i^{\ n-1}\right)\right)a_j^{\ n-1} \quad (10)$$

and assuming correct decoding:

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$$\Delta h_{ij}^{\ n} = \left(\sum_{l=1}^{p}\left(h_{il}^{\ n-1} - \hat{h}_{il}^{\ n-1}\right)s_l^{\ n-1}\right)a_j^{\ n-1} + m_i^{\ n-1}a_j^{\ n-1}$$
$$= \beta\varepsilon_{ij}^{\ n-1} + \sum_{\substack{l=1\\ l\neq j}}^{p}\varepsilon_{il}^{\ n-1}.s_l^{\ n-1}.a_j^{\ n-1} + m_i^{\ n-1}a_j^{\ n-1} \qquad (11)$$

Where $\varepsilon_{ij}^{n-1} = h_{ij}^{n-1} - \hat{h}_{ij}^{n-1}$ and β is the product of the s_j^{n-1} and a_j^{n-1} terms [23]. The elements of the updated channel can be written as:

$$\hat{h}_{ij}^{\ n} = \hat{h}_{ij}^{\ n-1} + k_{ij}\Delta h_{ij}^{\ n} \qquad (12)$$

$$\hat{h}_{ij}^{\ n} = \hat{h}_{ij}^{\ n-1} + \beta k_{ij}\varepsilon_{ij}^{\ n-1} + k_{ij}\sum_{\substack{l=1\\ l\neq j}}^{p}\varepsilon_{il}^{\ n-1}s_l^{\ n-1}a_j^{\ n-1} + k_{ij}m_i^{\ n-1}a_j^{\ n-1} \qquad (13)$$

Assuming white data, the probability density function of the third term of (13) is approximately Gaussian. The last two terms in (13) can be approximated by white noise with average power [24]:

$$\overline{N}_{0,j} = \frac{N_0}{\rho_j}\left(1 + \sum_{\substack{l=1\\ l\neq j}}^{p} e_l\right) \qquad (14)$$

Where N_0 is the original total white noise power for the receive antenna i, e_l is the average error covariance reduction value and ρ_j is a constant that specifies the fraction of noise associated with stream j. The optimum value of k_{ij} is the one that minimises the value $\sigma^2 = E\left[\left|h_{ij}^{\ n} - \hat{h}_{ij}^{\ n}\right|^2\right]$.

In our derivation of the optimum **K** parameters we adopt Clarke's power spectrum density ($P(f)$) defined for a maximum Doppler shift f_D as [25]:

$$P(f) = \begin{cases} \dfrac{1}{\pi f_D}\dfrac{1}{\sqrt{1-\left(\dfrac{f}{f_D}\right)^2}}, & |f| < f_D \\ 0, & otherwise \end{cases} \qquad (15)$$

We calculate the optimum set of **K** parameters by differentiating σ^2 with respect to k_j and setting the derivative equal to zero. After some lengthy but straight forward mathematical manipulation and assuming the receiver antennas are uncorrelated with equal average SNR, the optimum set of **K** parameters is given by:

$$k_{ij} = k_j \quad \forall i \qquad (16)$$

$$k_j = 3.6\sqrt[3]{\frac{\rho_j (f_D T_s)^2}{\beta N_0 (1 + \sum_{\substack{l=1\\ l\neq j}}^{p} e_l)}} = 3.6\sqrt[3]{\frac{(f_D T_s)^2}{N_0 (1 + \sum_{\substack{l=1\\ l\neq j}}^{p} e_l)}} \qquad (17)$$

$$e_j \approx \frac{0.75}{p}k_j \qquad (18)$$

$$N_0 = \frac{1}{E_s/N_0} \qquad (19)$$

Where T_s is the symbol duration.

We define E_s/N_0 as the total SNR if all transmitting antennas transmit the same symbol. In (17) β is equal to $1/p$ [23] and we set and ρ_j equal to $1/p$ since we assume equal average transmit (receive) power for each transmit (receive) antenna. The k_j parameters are calculated recursively. First we assume no interference from the other symbols and set $e_j = 0$. We then calculate k_1 and update e_1. Next we substitute the new value of e_1 for k_2 then update e_2. This process is repeated till all the k_j and e_j parameters are calculated and then we repeat the calculations again. This process converges very quickly and the final values of k_j are not very different from the initial ones. The k_j parameters then can be used to update the channel estimate. The algorithm requires the calculation of p k_j parameters, one for each transmit antenna using equations (18) and (19). These can be calculated once at the beginning of the packet and held constant for the duration of the packet. $\mathbf{\Delta H}_n$ requires the pseudo inverse of the ($p\times 1$) vector $\mathbf{s}$, which can be pre-computed and stored, and then multiplying it by the term $\left(\mathbf{r}_{n-1} - \hat{\mathbf{H}}_{n-1}\hat{\mathbf{s}}_{n-1}\right)$, equation (6), which is calculated in the VBLAST algorithm. This multiplication consists of $p\times q$ complex multiplications. The channel update, equation (8), requires $p\times q$ real by complex multiplications and $p\times q$ complex additions.

For MIMO-OFDM systems, the performance is further degraded by ICI. The ICI power can be considered as white noise. Hence the total noise power (N_T) becomes [26] at subcarrier m.

$$N_T = \sum_{\substack{l=1\\ l\neq j}}^{p} e_l^{\ 2}(m) + 2p(2\pi f_d T_s)^2 \sum_{\substack{p=0\\ p\neq m}}^{N-1}\left|C_{pm}\right|^2 + \frac{N_0}{E_s} \qquad (20)$$

Where j is the index of the transmit antenna to be decoded, f_d is the Doppler shift and C_{pm} is given by:

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$$C_{pm} = \frac{1}{N}\sum_{n=0}^{N-1} n.e^{i\frac{2\pi}{N}n(p-m)} \qquad (21)$$

N is the number of subcarriers, i is the square root of -1, e is the natural number. $e_l(m)$ is given by:

$$e_l^2(m) = 2\left[\frac{\pi f_d T_s(N+CP)}{k_j^{opt}}\right]^2 + \frac{k_j^{opt}}{2}N_T \qquad (22)$$

The optimum update parameter is then given by:

$$k_j^{opt} = \sqrt[3]{\frac{8[\pi f_d T_s(N+CP)]^2}{N_T}} \qquad (23)$$

CP is the length of the cyclic prefix.

Table 1.
Calculation of k_j parameters algorithm

CALCULATION OF k_j PARAMETERS ALGORITHM
1) set $e_j = 0$ for all j
2) iteration = 1
3) j = 1
4) calculate k_j using equation (17) or (23)
5) calculate e_j using equation (18) or (22)
6) j = j+1
7) if (j < number of transmit antennas) go to 4
8) iteration = iteration +1
9) if (iteration < max number of iterations) go to 3

Table 2.
Channel update algorithm

CHANNEL UPDATE ALGORITHM
1) calculate the k_j parameters
2) calculate **ΔH** *using equation (6)*
3) update the channel using equation (8)

IV. Simulation Model And Results

Numerous channel models to simulate wireless channels exist [27-31] but the ring model is the most common. The ring model was designed to simulate mobile-basestation links with dense environment around the mobile terminal. A two ring model was proposed in [27] for vehicular networks, however, it is not realistic for cars on motorways since the number of surroundings will be small. Instead we use the elliptical model proposed in [32] and shown in Fig (2).

The dimensions of the ellipse can be calculated from the delay spread of the channel [29]. In [31, 33] the delay spread for VANET was measured for the city and on highways and the minimum mean delay spread was 109ns.

We adopt this value in our model since as the delay spread increases the distribution of the angle of arrival (AOA) at the receiver approaches uniform distribution in [0, 2π) which is ideal for VBLAST since low correlation between the antennas can be achieved [34]. We further assume no line of sight exists, due to cars between the communicating nodes, and the distance is 1km.

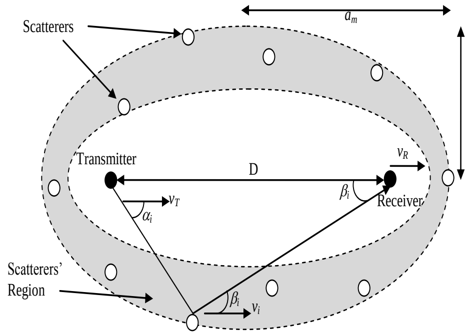

Fig 1. Elliptical Channel model

We ran a number of simulations using Matlab to study the performance of the algorithm. In our simulations we use 2×4 and 3×4 VBLAST systems, 1MSymbol/s, 5.9GHz and the channel model shown in Fig (2). OFDM simulation for 2×4 and 3×4 VBLAST had 64 subcarriers and 10MHz bandwidth. In the simulations, initially the algorithm will have perfect channel knowledge rather than estimating from a training sequence to isolate any errors that might arise from the use of training sequence estimation. The optimum update parameters (k_{opt}) are shown in figures (4.1) and (4.2) for 2 and 3 transmitting antennas respectively. At low SNR and/or low speeds, the update parameters take small values to reduce the effects of noise. As the SNR and speed increase the parameters increase to provide better channel tracking. As the number of antennas increase, the interference increases thus leading to lower parameter values. If all streams have equal power, the optimum update parameters (k_j) will be equal for all j. Fig (3) shows the MSE in the estimated channel for the cases of 256, 512 and 1024 symbols per antenna using QPSK modulation with channel update, using equation (7) and (16) to (18), compared to 256 without update. As can be seen from Fig (2) the update algorithm reduces the MSE by 50% at 12dB Es/N_0. The MSE in Fig (3) without update does not depend on the SNR because the receiver is assumed to have perfect, noise free, estimate of the channel at the beginning of the packet and this is held constant for the duration of the packet.

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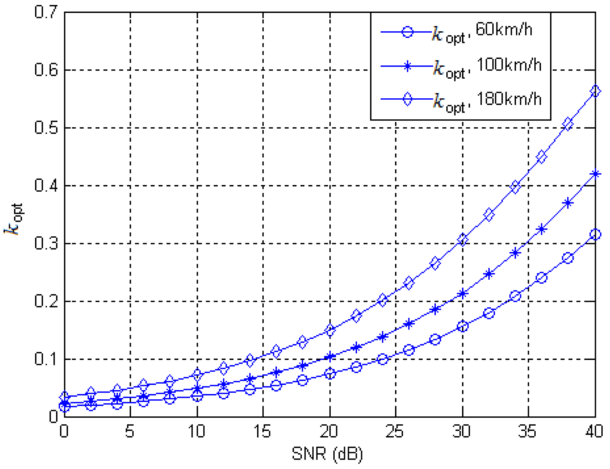

Fig 2. k_{opt} for Two Transmitting Antennas vs. SNR

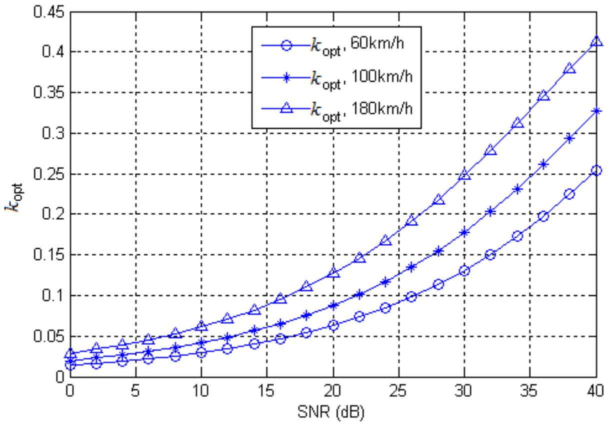

Fig 3. k_{opt} for Three Transmitting Antennas vs. SNR

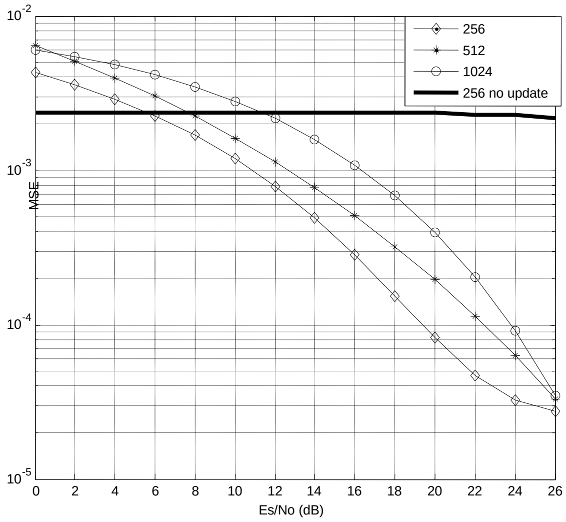

Fig 4. MSE of Channel Estimation for 180 km/h

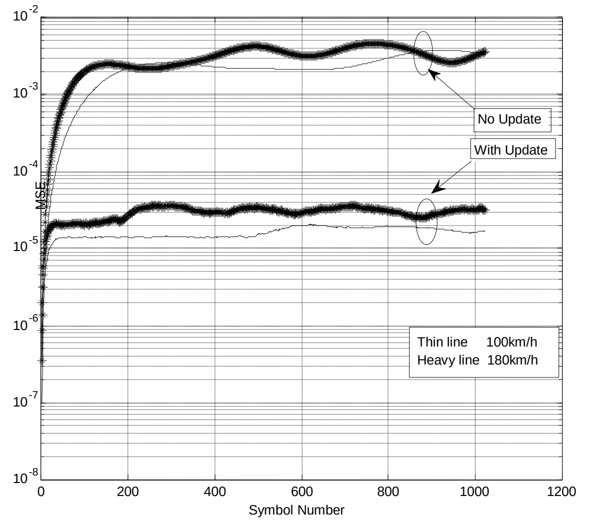

Fig 5. MSE of Channel Estimation vs. No of symbols

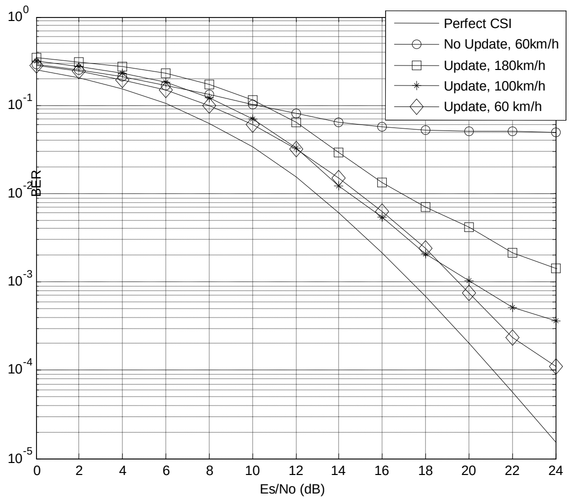

Fig 6. QPSK BER with and without channel update

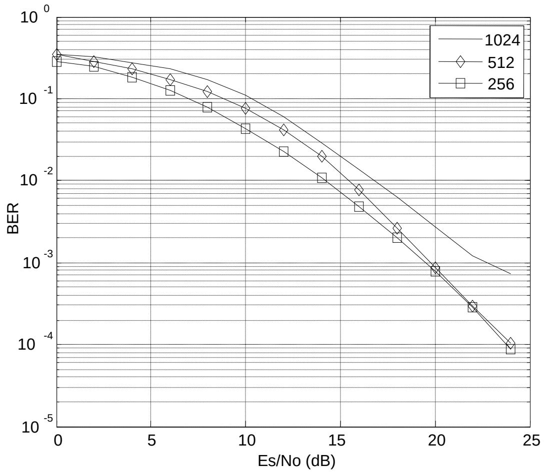

Fig 7. BER for different packet sizes, 60 km/h

Fig (4) shows the MSE vs. the symbol number for 26dB E_s/N_0. Initially the receiver will have perfect channel knowledge (MSE ≈ 0) but with time this estimate becomes invalid due to the high Doppler shift. Fig (5) shows the BER performance of QPSK for various relative vehicle speeds. As can be seen the performance improves considerably when the algorithm is used and is 2dB from that of perfect channel knowledge for 60km/hr.

Fig (6) shows the performance of the same system using QPSK with various packet lengths for a speed of 60 km/hr. As can be seen from the figure, the performance degrades as the packet length increases; this is due to two reasons. The first reason is estimation error, as the estimation process proceeds, the error in the estimation accumulates and for long packets this will lead to erroneous results near the end of the packet. The second reason is detection errors since the probability of symbol errors increases as the packet length increases. The estimation algorithm assumes correct decoding; therefore such errors will affect the performance of the algorithm.

Fig (8) is a comparison between BER performance with the initial Channel State Information (CSI) matrix obtained via a training sequence and BER with perfect initial CSI for 256 symbols per transmit antenna. The optimum training sequence for B transmit antennas at high speeds is a $B \times B$ orthogonal matrix as proven in [35]. The element ($s_{m,n}$) at position (m, n) of the optimum training matrix ($\mathbf{S}_{tr}$) is calculated by equation (20) as proposed in [35] yielding the training matrices shown in equation (21) for $B = 2$ and (22) for $B = 3$. As can be seen from Fig (4), the use of a training sequence for initial channel estimation degrades the performance compared to the performance using perfect initial CSI. However the channel update algorithm still provides superior performance compared to the training only case which experiences an error floor, see Fig (6).

$$s_{m,n} = \frac{1}{\sqrt{B}} e^{-j\frac{2\pi}{B}(m-1)(n-1)} \qquad (20)$$

$$\mathbf{S}_{tr} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad (21)$$

$$\mathbf{S}_{tr} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & -\frac{1}{2}-\frac{\sqrt{3}}{2}j & -\frac{1}{2}+\frac{\sqrt{3}}{2}j \\ 1 & -\frac{1}{2}+\frac{\sqrt{3}}{2}j & -\frac{1}{2}-\frac{\sqrt{3}}{2}j \end{bmatrix} \qquad (22)$$

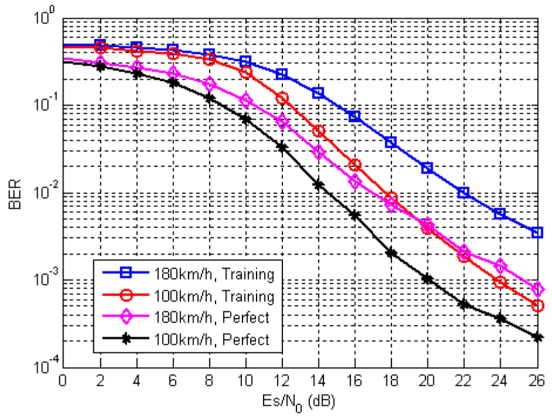

Fig 8. BER Comparison Using Perfect and Training-Based Initial CSI

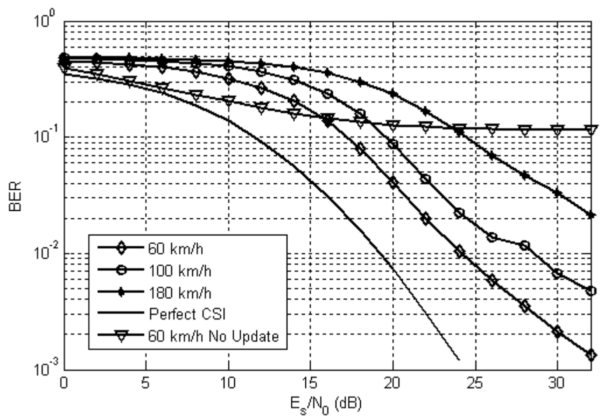

Fig 9. BER Performance of 3×4 VBLAST with and without Channel Update

Fig (9) shows the performance of 3×4 VBLAST with the training sequence of equation (22). From the figure we observe the performance of VBLAST with the channel update algorithm at high SNR is superior to channel estimation using only a training sequence (with perfect initial CSI) which experiences an error floor.

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Fig (10) and Fig (11) show the BER performance of VBLAST-OFDM with 64 subcarriers. As can be seen at low SNR the performance without update is better than when using the update algorithm. This is due to the high noise power which affects the algorithm in two ways. First the high noise is directly affecting the channel estimate of the update algorithm, second at low SNR the probability of error is higher, and since the algorithm assumes correct decoding, the estimate of the channel will not be accurate. At high SNR the BER performance of the channel update algorithm is superior to the no update case, approximately 10^{-1} and 10^{-2} at 40dB for 3×4 and 2×4 respectively. Without update, the BER drops as the speed increases due to the change in the channel and the ICI. The proposed channel update tracks the changes in the channel and takes into account the ICI, thus reducing the error and improving the BER. Both methods (i.e. with and without update) however experience an error floor due to the ICI.

V. CONCLUSION

In this paper we developed a simple recursive algorithm to keep track of changes in fast fading channels and update the channel estimation matrix for single and multicarrier MIMO systems. The proposed algorithm improves the BER and channel estimate MSE and has a low computational complexity because it uses only first order Kalman filters. Simulation results showed considerable improvements in BER and MSE when using the update algorithm compared to the training only channel estimation for single and multicarrier systems. OFDM systems, however, experience an error floor at high speeds due to ICI.

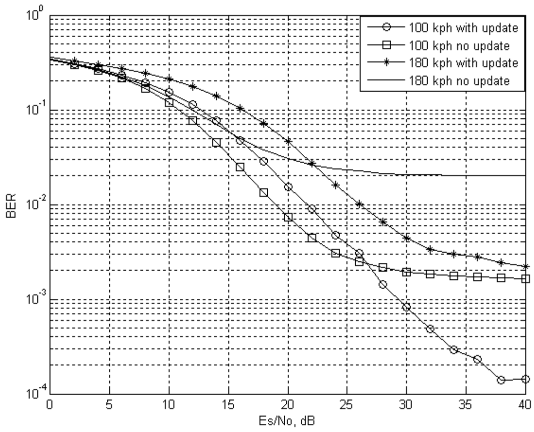

Fig (10): BER performance of 3×4 with and without channel update

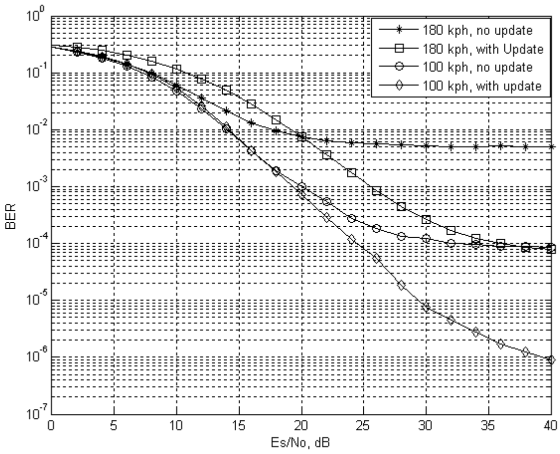

Fig (11): BER performance of 2×4 with and without channel update

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