CHANNEL TRACKING FOR VBLAST

Updating the Channel Estimation in a Flat-Fading Channel

Ghassan Abdalla, Mosa Ali Abu-Rgheff, and Sidi-Mohammed Senouci

Vehicular networks require accurate channel state information (CSI) to decode the received signal. Such knowledge is usually estimated using short training sequences. However, in vehicular networks, the channel coherence time is very small due to the high speeds of the nodes, therefore the channel estimate from the training is likely to become inaccurate as the decoding proceeds. Using shorter packets can improve the performance at the cost of increased overhead. In this article, we introduce a novel channel tracking algorithm for vertical Bell Labs layered space-time (VBLAST) in vehicular networks with no change in the overhead. The algorithm uses a set of first order Kalman filters, therefore it has less complexity compared to existing tracking methods that use higher order filters. The developed algorithm uses the decoded symbols and the received signal after the VBLAST decoding process to improve the channel estimate. Simulation results show considerable improvement in mean square error (MSE) and bit error rate (BER) when using this algorithm compared to channel estimation by training only with a small increase in hardware complexity. The capacity of multiple-input, multiple-output (MIMO) systems was shown to increase with the number of antennas [1]. Several algorithms have been developed to achieve part of this capacity, 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 making it possible to use higher modulations to achieve higher data rates. BLAST systems, on the other hand, assume the receive antennas are in a rich Rayleigh fading environment causing each antenna to receive an independent signal.

Digital Object Identifier 10.1109/MVT.2009.931842

VBLAST makes use of the channel state matrix (**H**) to decode the signal recursively. It starts decoding the signal that has the highest signal-to-noise ratio (SNR) then cancels its contribution (interference) from the received signal vector, thus achieving better performance than the zero forcing receiver. Other BLAST algorithms exist such as

 1556-6072/09/$25.00©2009IEEE

IN VEHICULAR NETWORKS, THE CHANNEL COHERENCE TIME IS VERY SMALL DUE TO THE HIGH SPEEDS OF THE NODES, THEREFORE THE CHANNEL ESTIMATE FROM THE TRAINING IS LIKELY TO BECOME INACCURATE AS THE DECODING PROCEEDS.

diagonal, horizontal, and turbo BLAST, but they require more complicated transmitters and/or receivers than VBLAST [2]–[4].

In a vehicle ad hoc network (VANET), vehicles communicate in an ad hoc mode while moving at high speeds, therefore relative speeds of 200 km/h or more between cars in opposite directions are not uncommon. The frequency band allocated for VANET networks is at 5.9 GHz leading to a Doppler shift of 1,100 Hz for 200 km/h speed, and a channel coherence time of approximately 162 μs [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 short time.

In this article, we introduce an algorithm to update the channel estimation in a flat fading channel. We assume an initial estimate of the channel is available, possibly from a training sequence, and the algorithm enhances this estimation 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 SNR.

Related Work

Channel estimation has been of interest for many research works. In [6]–[9], the optimum training sequence for MIMO systems has been investigated. In [6]–[9], it was shown that an orthonormal training set is the optimum training sequence for MIMO channels. These can be used to obtain an initial estimate of the channel. In [10], 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. In [11], a maximum likelihood channel tracking algorithm has been proposed. The authors modeled the channel as an auto regressive (AR) process using Clarke's power spectral density. A combination of a Kalman filter and a minimum mean square error decision feedback equalizer (MMSE-DFE) was used in [12] 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 [13], an AR moving average (ARMA) filter was developed to model the channel response based on Clarke's channel power spectral density, this was then used to design a Kalman filter for channel tracking. In this article, we use a bank of first order Kalman filters for channel updating, thus avoiding the computation complexity encountered in these algorithms. The proposed algorithm recursively estimates the change in the channel and updates the channel matrix to minimize the estimate error, thus improving the BER performance.

Capacity of VBLAST

The theoretical capacity (C) of VBLAST has been studied in [14]. It was shown that for a given SNR (ρ) per receive antenna, the optimum ratio of the number of transmit to receive antennas (α) is the one that maximizes the expression

$$C \approx \max_{0<\alpha<1}\{\alpha \cdot \log_2[1 + \rho(\alpha^{-1} - 1)]\}. \qquad (1)$$

Note that the number of transmit antennas is always less than that of receive antennas to provide diversity. Figure 1 is a comparison between the theoretical capacity, using (1), and the capacity obtained from simulations. We assume a 1 MHz bandwidth and 3×4 VBLAST system using quadrature amplitude modulation (QAM) with perfect channel knowledge at the receiver and optimize the number of transmit antennas, modulation, and symbol rate to maximize the capacity while maintaining a maximum BER of 10^{-3} for uncoded data and 10^{-4} when using the 802.11a standard rate 1/2 convolutional code. The capacity for the optimized values from simulations is given by (2).

$$C = \frac{q \times Bs \times Rs \times Cr}{p \times B}, \qquad (2)$$

where p is the number of transmit antennas, q is the number of receive antennas, Bs is the number of bits per symbol, Rs is the symbol rate, Cr is the code rate, and B is the bandwidth. These parameters are determined by simulation and are used in (2) to find the optimized capacity plotted in Figure 1.

As can be seen from Figure 1, it is possible to achieve high capacities by using VBLAST. At 20 dB, a maximum of 2.4 b/s/Hz/dimension is achievable without coding, 3.6 b/s/Hz/dimension with coding compared to the theoretical value of 3.8 b/s/Hz/dimension from (1). The simulation results increase in a staircase manner since the QAM constellation increases in multiples of two. To achieve this high capacity, however, accurate channel state information matrix is required at the receiver. As the channel varies with time, the channel matrix must be updated frequently to ensure correct decoding. In the next section, we develop an algorithm to track the changes in the channel and update the channel matrix at the receiver.

Derivation of the Channel Update Algorithm

For a $p \times q$ VBLAST system in a flat fading channel, the length q column vector of received signal ($\mathbf{r}_{n-1}$) at time index $n-1$ can be written as

$$\mathbf{r}_{n-1} = \mathbf{H}_{n-1}\mathbf{s}_{n-1} + \mathbf{m}_{n-1}. \tag{3}$$

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 length q column vector of white noise all at time $n-1$. Throughout this article, lower and upper case bold characters represent vectors and matrices respectively while lower case characters represent scalars and elements within the matrix/vector. The symbol $(.)^+$ represents the Moore-Penrose pseudo inverse process.

Let the estimated channel matrix at time $n-1$ be $\hat{\mathbf{H}}_{n-1}$. Ignoring the noise, the simplest VBLAST 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

$$\hat{\mathbf{s}}_{n-1} = \hat{\mathbf{H}}^+_{n-1} \times \mathbf{r}_{n-1}, \tag{4}$$

since for a full rank $q \times p$, $p \leq q$ matrix $\mathbf{H}$ we have [15]

$$\mathbf{H}^+\mathbf{H} = \mathbf{I_p}. \tag{5}$$

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

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

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

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

Note that the term $(\mathbf{r}_{n-1} - \hat{\mathbf{H}}_{n-1}\hat{\mathbf{s}}_{n-1})$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 estimate as

$$\hat{\mathbf{H}}_n = \hat{\mathbf{H}}_{n-1} + \mathbf{K} \cdot \Delta\mathbf{H}_n, \tag{8}$$

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 we assume the receive antennas are not correlated, we need to optimize $\mathbf{K}$ for only one antenna. Equation (7) can be rewritten for the elements of the matrix $\Delta\mathbf{H}_n$ as

OTHER BLAST ALGORITHMS EXIST SUCH AS DIAGONAL, HORIZONTAL, AND TURBO BLAST, BUT THEY REQUIRE MORE COMPLICATED TRANSMITTERS AND/OR RECEIVERS THAN VBLAST.

$$\Delta h^n_{ij} = \left(r^{n-1}_i - \sum_{l=1}^{p} \hat{h}^{n-1}_{il} \,.\, \hat{s}^{n-1}_l \right) a^{n-1}_j, \tag{9}$$

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

$$\Delta h^n_{ij} = \left(\sum_{l=1}^{p} (h^{n-1}_{il} \cdot s^{n-1}_l - \hat{h}^{n-1}_{il} \cdot \hat{s}^{n-1}_l + m^{n-1}_i) \right) a^{n-1}_j \tag{10}$$

and assuming correct decoding

$$\begin{aligned} \Delta h^n_{ij} &= \left(\sum_{l=1}^{p} (h^{n-1}_{il} - \hat{h}^{n-1}_{il}) \cdot s^{n-1}_l \right) a^{n-1}_j + m^{n-1}_i a^{n-1}_j \\ &= \beta \varepsilon^{n-1}_{ij} + \sum_{l=1,\, l \neq j}^{p} \varepsilon^{n-1}_{il} \cdot s^{n-1}_l \cdot a^{n-1}_j + m^{n-1}_i a^{n-1}_j, \end{aligned} \tag{11}$$

where $\varepsilon^{n-1}_{ij} = h^{n-1}_{ij} - \hat{h}^{n-1}_{ij}$ and β is the product of the s^{n-1}_j and a^{n-1}_j terms [14]. The elements of the updated channel can be written as

$$\hat{h}^n_{ij} = \hat{h}^{n-1}_{ij} + k_{ij}\Delta h^n_{ij} \tag{12}$$

$$\begin{aligned} \hat{h}^n_{ij} = \hat{h}^{n-1}_{ij} &+ \beta\, k_{ij}\varepsilon^{n-1}_{ij} + k_{ij} \sum_{l=1,\, l \neq j}^{p} \varepsilon^{n-1}_{il} s^{n-1}_l a^{n-1}_j \\ &+ k_{ij} m^{n-1}_i a^{n-1}_j. \end{aligned} \tag{13}$$

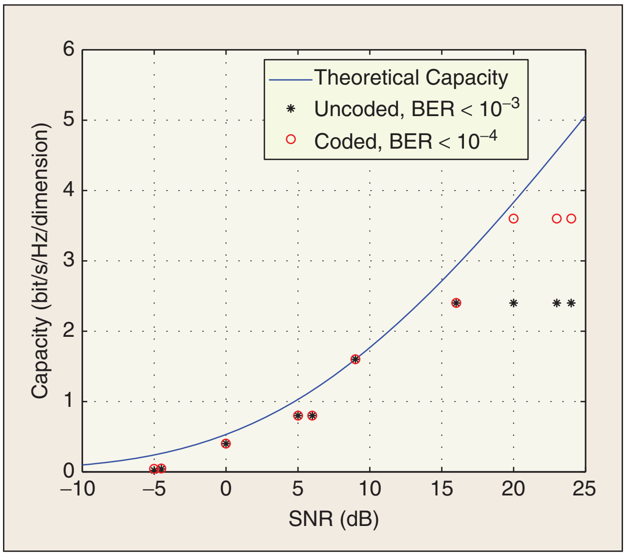

FIGURE 1 Achievable capacity using 3×4 VBLAST.

THE ESTIMATION ALGORITHM ASSUMES CORRECT DECODING; THEREFORE SUCH ERRORS WILL AFFECT THE PERFORMANCE OF THE ALGORITHM.

An analysis of the probability density function of the third term of (13) shows that it is approximately Gaussian. The last two terms in (13) can then be approximated by white noise with average power [16]

$$\overline{N}_{0,j} = \frac{M_0}{\rho_j}\left(1 + \sum_{l=1,\, l\neq j}^{p} e_l\right), \tag{14}$$

where M_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 minimizes the value $\sigma^2 = E[|h_{ij}^n - \hat{h}_{ij}^n|^2]$.

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 [17]

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

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

$$k_{ij} = k_j \quad \forall i \tag{16}$$

TABLE 1 ***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 (17).
5) Calculate e_j using (18).
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.***

1) Calculate the k_j parameters.
2) Calculate ΔH using (6).
3) Update the channel using (8).

$$k_j = 3.6\sqrt[3]{\frac{\rho_j (f_D T_s)^2}{\beta M_0\left(1 + \sum_{l=1,l\neq j}^{p} e_l\right)}} = 3.6\sqrt[3]{\frac{(f_D T_s)^2}{M_0\left(1 + \sum_{l=1,l\neq j}^{p} e_l\right)}} \tag{17}$$

$$e_j \approx \frac{0.75}{p} k_j \tag{18}$$

$$M_0 = \frac{1}{E_s/N_0}, \tag{19}$$

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 $1/p$ [15] and we set 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 and update e_2. This process is repeated until all of the k_j and e_j parameters are calculated and then we repeat the calculations again with the new e_j values. This process converges very quickly. The k_j parameters then can be used to update the channel estimate. The algorithm is summarized in Tables 1 and 2. The update algorithm requires the calculation of p k_j parameters, one for each transmit antenna using (18) and (19). These can be calculated once at the beginning of the packet and held constant for the duration of the packet. $\Delta\mathbf{H}_n$ requires the pseudo inverse of the $(p \times 1)$ vector $\mathbf{s}$, which can be precomputed and stored, and then multiplied by the term $(\mathbf{r}_{n-1} - \hat{\mathbf{H}}_{n-1}\hat{\mathbf{s}}_{n-1})$, shown in (6), which is calculated in the VBLAST algorithm. This multiplication consists of $p \times q$ complex multiplications. The channel update, shown in (8), requires $p \times q$ real by complex multiplications and $p \times q$ complex additions.

Simulation Model and Results

Numerous channel models to simulate wireless channels are available in [18]–[21] but the ring model is the most common. The ring model was designed to simulate mobile-base station links with dense environment around the mobile terminal. A two-ring model was proposed in [18] for vehicular networks, however, such a model is not realistic for cars on motorways since the number of surroundings will be small. Instead we use the elliptical model proposed in [21] and shown in Figure 2 modified for the high-speed nodes.

The dimensions of the ellipse can be calculated from the delay spread of the channel [20]. In [22] and [23], the delay spread for VANET was measured for the city and on highways and the minimum mean delay spread was 109 ns. 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 $[0, 2\pi)$. This distribution is ideal for VBLAST since low correlation between the antennas can be achieved [24]. We further assume no line of sight exists, due to cars between the communicating nodes, and the distance is 1 km.

We ran a number of simulations using MATLAB to study the performance of the algorithm. In our simulations, we use a 2×4 VBLAST system 1M Symbol/s, 5.9 GHz and the channel model shown in Figure 2. In the simulations, initially the algorithm will have perfect channel knowledge rather than estimating from a training sequence. This is necessary to isolate any errors that might arise from the use of training sequence estimation. We use the k_j values calculated from a single iteration to reduce the complexity. The receiver decodes the signal then uses the outcome of the decoding process in the channel update, therefore the algorithm will be affected by decoding errors. Figure 3 shows the MSE in the estimated channel for the cases of 256, 512, and 1,024 symbols per packet per antenna using quadrature phase shift keying (QPSK) modulation with the channel update algorithm compared to 256 without update. As can be seen from Figure 3, the update algorithm reduces the MSE by 50% at 12 dB Es/N_0. The MSE in Figure 3 without update does not depend on the SNR because the receiver is assumed to have a perfect, noise free, estimate of the channel at the beginning of the packet, and this is held constant for the duration of the packet.

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

Figure 6 shows the performance of the same system with various packet lengths for a speed of 60 km/h. Figure 6 proves 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

THE RECEIVER DECODES THE SIGNAL THEN USES THE OUTCOME OF THE DECODING PROCESS IN THE CHANNEL UPDATE, THEREFORE THE ALGORITHM WILL BE AFFECTED BY DECODING ERRORS.

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 incorrect symbol detection within a packet increases as the packet length increases. The estimation algorithm assumes correct decoding; therefore such errors will affect the performance of the algorithm.

Finally Figure 7 is a comparison between BER performance with the initial CSI obtained via a training sequence and BER with perfect initial CSI for 256 symbols per transmit antenna. The optimum training sequence for two transmit antennas at high speeds is a 2×2 orthogonal matrix as proven in [9]. We chose the training matrix ($\mathbf{S}_{tr}$)

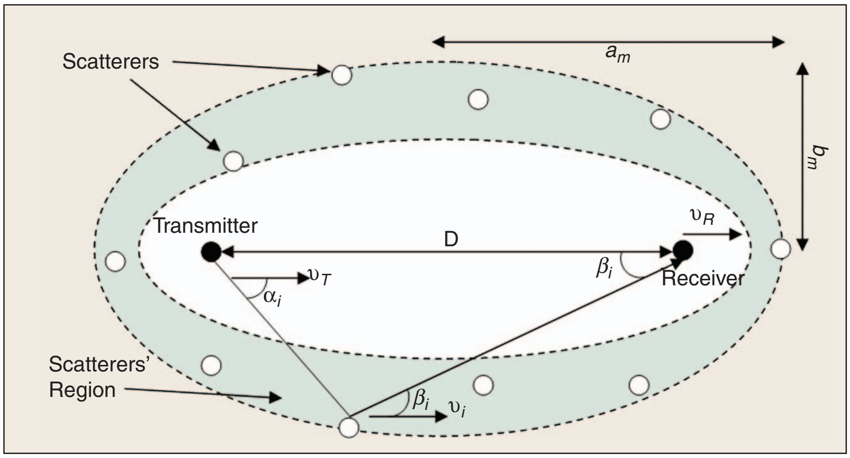

FIGURE 2 Elliptical channel model.

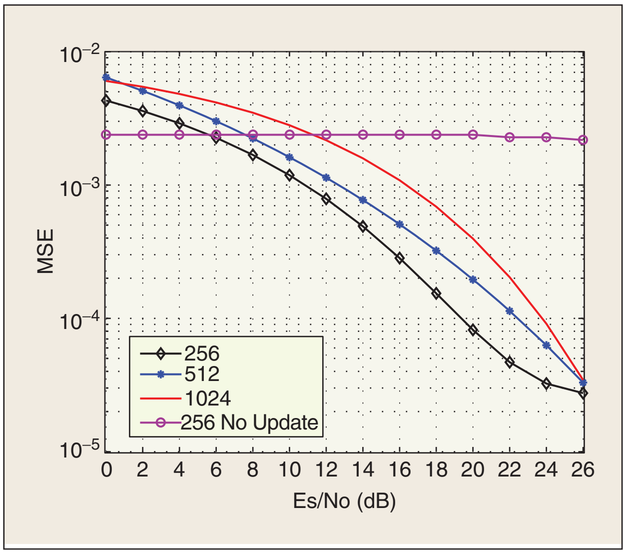

FIGURE 3 MSE of channel estimation for 180 km/h.

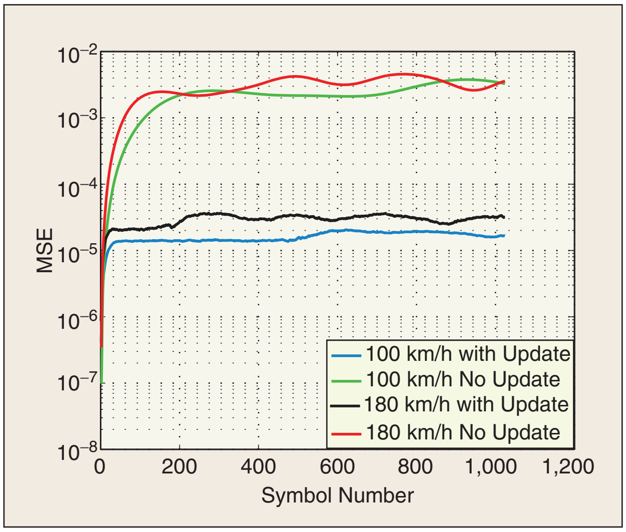

FIGURE 4 Average MSE of channel estimation versus number of symbols at 26 dB SNR.

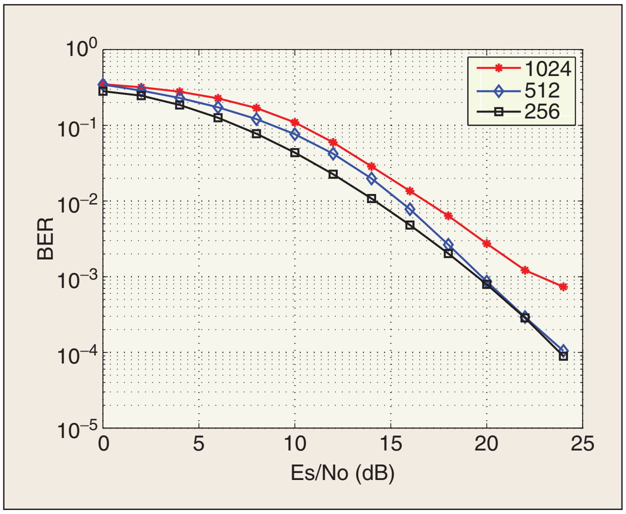

FIGURE 6 QPSK BER for different packet sizes, 60 km/h.

proposed in [9] and shown in (20). As can be seen from Figure 7, the use of a training sequence for initial channel estimation reduces the performance compared to perfect initial CSI. However, the channel update algorithm still provides superior performance compared to the training only case that experiences an error floor (Figure 5)

$$\mathbf{S}_{tr} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \tag{20}$$

Conclusions

In this article, we have developed a simple recursive algorithm to keep track of changes in the channel and to update the channel estimation matrix for VBLAST. The update algorithm enhances the channel estimation on a symbol by symbol basis, but this can be relaxed for high symbol rates and/or slow fading as the channel coherence time will be large compared to the symbol duration. The proposed algorithm improves system BER and channel estimate MSE via continuous and accurate channel updating and has less computational complexity compared to existing tracking algorithms as a result of using a simplified Kalman filter. Simulation results showed remarkable improvements when using the update algorithm compared to the training only channel estimation. The algorithm is capable of updating the channel estimation for VBLAST for nodes moving at high speeds, thus improving the BER of VANET. Further work is ongoing to extend the algorithm to frequency selective fading and OFDM.

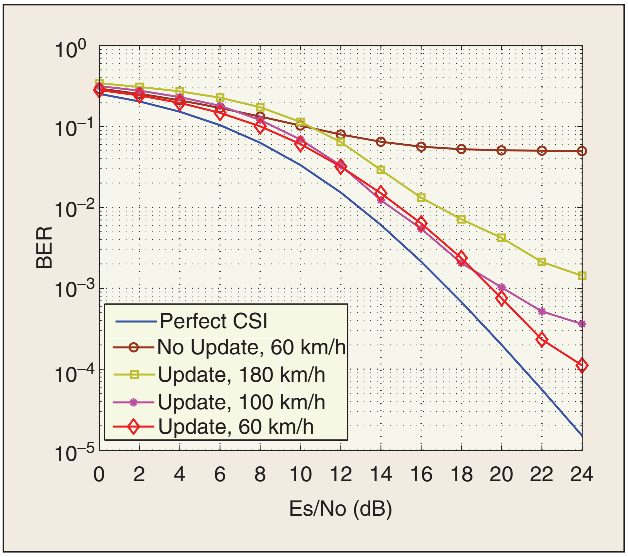

FIGURE 5 QPSK BER with and without channel update.

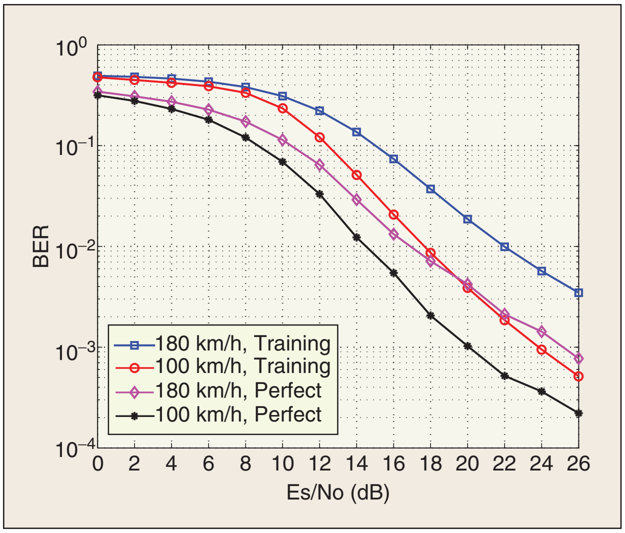

FIGURE 7 BER comparison between perfect initial CSI and using training sequence.

Acknowledgment

The authors would like to thank France Telecom and the University of Plymouth for supporting this work.

Author Information

Ghassan Abdalla (ghassan.abdalla@plymouth.ac.uk) received his B.Sc degree in electrical engineering from the University of Khartoum, Sudan in 2003 and his M.Sc. degree in digital communication systems from Loughborough University in 2006. He is currently working towards his Ph.D. degree in mobile communications at the University of Plymouth, U.K. His research interests include MIMO and OFDM systems, wireless channel modeling, channel estimation, antenna design, radio propagation, and medium access control layer design and analysis.

Mosa Ali Abu-Rgheff (mosa@plymouth.ac.uk) is currently Reader in mobile communications at the University of Plymouth U.K. He received his B.Sc. degree (with honors) in electronic and electrical engineering from the University of Leeds U.K., and his Ph.D. degree from the University of Bradford, U.K. on work on parametric amplifiers. He is leading the mobile communication networks research at the Faculty of Technology. His research interests include wireless communications, vehicle ad hoc networks, and cognitive radio systems. He is the author of one book and is in the process of writing another. He served on U.K. Engineering and Physical Sciences Research Council (EPSRC) Peer Review College and on EPSRC Communications Panel. He is a Charted Engineer, Member of U.K. Engineering Council, Member of IET, and Senior Member of the IEEE.

Sidi-Mohammed Senouci (sidimohammed.senouci@orange-ftgroup.com) received the M.S. degree in artificial intelligence, from the University of Paris 13, and the Ph.D. degree in computer science from the University of Paris 6 in 1999 and 2003, respectively. From 2002 to 2004, he was an associate lecturer in the University of Cergy-Pontoise, France. In 2004, he was a research expert at France Telecom R&D (Orange Labs) Lannion, France. He now leads France Telecom projects and is involved in different French and European projects dealing with spontaneous, pervasive, and vehicular networks.

SIMULATION RESULTS SHOWED REMARKABLE IMPROVEMENTS WHEN USING THE UPDATE ALGORITHM COMPARED TO THE TRAINING ONLY CHANNEL ESTIMATION.

References

[1] S. Haykin and M. Moher, *Modern Wireless Communications*. Englewood Cliffs, NJ: Pearson Prentice Hall, 2005.

[2] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," in *Proc. IEEE Int. Symp. Signals, Systems, and Electronics*, Pisa, Italy, Sept. 1998, pp. 295–300.

[3] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Labs Tech. J.*, pp. 41–59, 1996.

[4] M. Sellathurai and S. Haykin, "TURBO-BLAST for wireless communications: Theory and experiments," *IEEE Trans. Signal Processing*, vol. 50, pp. 2538–2546, Oct. 2002.

[5] B. Sklar, "Rayleigh fading channels in mobile digital communication systems—Part I: Characterization," *IEEE Commun. Mag.*, vol. 35, no. 7, pp. 90–100, July 1997.

[6] M. Biguesh and A. B. Gershman, "Training-based MIMO channel estimation: A study of estimator tradeoffs and optimal training signals," *IEEE Trans. Signal Processing*, vol. 54, pp. 884–893, Mar. 2006.

[7] H. Minn and N. Al-Dhahir, "Optimal training signals for MIMO OFDM channel estimation," *IEEE Trans. Wireless Commun.*, vol. 5, no. 5, pp. 1158–1168, May 2006.

[8] B. Park and T. F. Wong, "Optimal training sequence in MIMO systems with multiple interference sources," in *Proc. IEEE Communications Society GLOBECOM 2004*, pp. 86–90.

[9] Q. Sun, D. C. Cox, H. C. Huang, and A. Lozano, "Estimation of continuous flat fading MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 1, pp. 549–553, Oct. 2002.

[10] B. Balakumar, S. Shahbazpanahi, and T. Kirubarajan, "Joint MIMO channel tracking and symbol decoding using Kalman filtering," *IEEE Trans. Signal Processing*, vol. 55, no. 12, pp. 5873–5879, Dec. 2007.

[11] E. Karami and M. Shiva, "Maximum likelihood MIMO channel tracking," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, May 2004, vol. 2, pp. 876–879.

[12] G. Yanfei and H. Zishu, "MIMO channel tracking based on Kalman filter and MMSE-DFE," in *Proc. IEEE Int. Conf. Communications, Circuits and Systems*, May 2005, vol. 1, pp. 223–226.

[13] L. Li, H. Li, H. Yu, B. Yang, and H. Hu, "A new algorithm for MIMO channel tracking based on Kalman filter," in *2007 Proc. IEEE Wireless Communications and Networking Conf. (WCNC)*, pp. 164–168.

[14] G. J. Foschini, G. D. Golden, R. A. Valenzuela, and P. W. Wolniansky, "Simplified processing for high spectral efficiency wireless communication employing multi-element arrays," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1841–1852, Nov. 1999.

[15] J. R. Schott, *Matrix Analysis for Statistics*. New York: Wiley, 1997.

[16] H. Meyr, M. Moeneclaey, and S. A. Fechtel, *Digital Communication Receivers*. New York: Wiley, 1998, pp. 723–769.

[17] W. C. Jakes, *Microwave Mobile Communications*. New York: IEEE, 1994.

[18] A. G. Zajic and G. L. Stuber, "A three-dimensional MIMO mobile-to-mobile channel model," in *Proc. 2007 IEEE Wireless Communications and Networking Conf. (WCNC)*, pp. 1885–1889.

[19] C. S. Patel, G. L. Stuber, and T. G. Pratt, "Simulation of Rayleigh-faded mobile-to-mobile communication channels," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1876–1884, Nov. 2005.

[20] R. B. Ertel, P. Cardieri, K. W. Sowerby, T. S. Rappaport, and J. H. Reed, "Overview of spatial channel models for antenna array communication systems," *IEEE Pers. Commun.*, vol. 5, no. 1, pp. 10–22, Feb. 1998.

[21] J. C. Liberti and T. S. Rappaport, "A geometrically based model for line-of-sight multipath radio channels," in *Proc. IEEE Vehicular Technology Conf.*, Atlanta, 1996, vol. 2, pp. 844–848.

[22] D. W. Matolak, I. Sen, W. Xiong, and N. T. Yaskoff, "5-GHz wireless channel characterization for vehicle-to-vehicle communications," in *Proc. IEEE Military Commun. Conf.*, 2005, pp. 3016–3022.

[23] A. Paier, J. Karedal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson. A. F. Molisch, and C. F. Mecklenbrauker, "Car-to-car radio channel measurements at 5 GHz: Pathloss, power-delay profile, and delay-Doppler spectrum," in *Proc. 2007 IEEE Int. Symp. Wireless Communication Systems (WCS) 2007*, pp. 224–228.

[24] D. Chizhik, F. Rashid-Farrokhi, J. Ling, and A. Lozano, "Effect of antenna separation on the capacity of BLAST in correlated channels," *IEEE Commun. Lett.*, vol. 4, pp. 337–339, Nov. 2000.

VT