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Full Length Research Paper

Space-time block-coded systems using numeric variable forgetting factor least squares channel estimator

Amit Grover[1] and Amit Kumar Kohli[2]*

[1]Department of Electronics and Communication Engineering, Shaheed Bhagat Singh College of Engineering and Technology, Ferozepur – 152002, Punjab, India.
[2]Department of Electronics and Communication Engineering, Thapar University, Patiala – 147004, Punjab, India.

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In this correspondence, the bit-error-rate (BER) performance evaluation of the space-time block-coded (STBC) communication systems using the numeric-variable-forgetting-factor (NVFF) least-squares (LS) channel estimator is presented. The polynomial channel paradigm is incorporated in LS algorithm in conjunction with NVFF to improve the channel tracking performance under the nonstationary wireless environment. The implementation of NVFF precludes the usage of LMS based VFF updating, and it also reduces the computational complexity. The simulation results are presented to demonstrate that the BER performance of STBC communication system using the linear least squares algorithm based channel estimator with NVFF outperforms the higher-order polynomial model-based and conventional VFF-based approaches, when M-ary QAM signal constellations are used for the wireless transmission.

Key words: Space-time block-codes, least squares algorithm, Rayleigh fading, Markov process, variable forgetting factor.

INTRODUCTION

Diversity techniques are of paramount significance in the wireless communication systems working over fading channels. But, the time-varying multipath fading is the fundamental phenomenon, which makes reliable wireless transmission difficult (Jakes, 1974). The most effective technique to mitigate multipath fading in a wireless channel is the transmitter power control, which requires a complex circuitry and control mechanism. The classical approach in the most scattering environments is to use the multiple antennas in order to improve the signal-to-noise-ratio (SNR) and the quality of received signal, which is a widely applied technique for reducing the effect of multipath fading. However the cost, size and power of the remote units (mobile) are major problems associated with the usage of receiver antenna diversity technique. Recently, different transmit antenna diversity approaches have been suggested as an economical solution to the aforementioned problems. A delay diversity scheme is proposed for a single base station (Seshadri and Winters, 1993; Winters, 1994), in which copies of the same symbol are transmitted through multiple antennas at different time intervals to create an artificial multipath distortion. This distortion is resolved to obtain diversity gain at the receiver by using maximum-likelihood-sequence-estimator (MLSE) or minimum-mean-squared-error (MMSE) equalizer. The use of transmit diversity in conjunction with array processing techniques for the interference excision has been presented for the space-time-trellis-codes (STTC) in (Tarokh et al., 1998), in which encoding of symbols across both the transmit antennas and the time intervals has been designed in trellis form. But, the high computation complexity of STTC emerged as its major drawback.

In order to exploit the embedded diversity for multiple transmissions, the transmit diversity scheme must rely on some additional processing. The pioneering work on employing multiple independent antennas has manifested

*Corresponding author. E-mail: drkohli_iitr@yahoo.co.in, akkohli@thapar.edu.

that the system capacity can dramatically increase with the number of antennas (Tech. Memo, 1995; Foscini and Gans, 1998). The space-time block-codes (STBCs) have appeared as a breakthrough in this emerging field of wireless communication, which allows high system performance with low cost mobile unit. Alamouti has proposed a scheme using two transmit antenna (Alamouti, 1998), that is, $N = 2$ and M receive antennas to provide a diversity order of $NM = 2M$. The application of redundancy in space across two-transmit antennas without bandwidth expansion provides diversity gain equal to maximal-ratio-receiver-combining (MRRC) diversity gain with two antennas at the receiver. Each transmit antenna in this scheme is to radiate the same energy as the single transmit antenna for MRRC. The perfect knowledge of mutually uncorrelated Rayleigh fading channels is assumed to be available at the receiver. This technique also excludes the requirement of any feedback from the receiver to the transmitter, which reduces the computational complexity akin to MRRC. The orthogonality of Alamouti's STBC imposes an artificial orthogonality on the channel, which provides maximum possible transmission rate by using remarkably simple MLSE algorithm based only on the linear processing at the receiver. It is noteworthy that the transmission rate is $R_{STBC} = K/P$, where P time slots are used to transmit K data symbols.

Tarokh et al. (1999a, b) have proposed a classical mathematical framework of orthogonal designs, which are applied to construct STBCs. A generalization of orthogonal designs has been shown to provide STBCs for both real and complex constellations for any number of transmit antennas. For full spatial diversity and full transmission rate, the complex orthogonal designs do not exist for four transmit antennas and even for higher configurations. However, the real orthogonal designs can exist only for two, four and eight transmit antennas. In case of complex constellations for more than two transmit antennas, there is a tradeoff between the full transmission rate and the full spatial diversity. In practice, the quasi-orthogonal designs provide higher transmission rates while sacrificing the full diversity. The simulation results and analytical analysis presented in Jafarkhani (2001) evidenced that the full transmission rate is more important for very low SNRs and high bit-error-rates (BERs), which can be achieved by using the quasi-orthogonal STBCs. On the contrary, the full diversity is the right choice for high SNRs and low BERs, which is a favorable condition for orthogonal STBCs. Therefore, the performance of quasi-orthogonal STBCs is inferior to the orthogonal STBCs under high SNRs, because the slope of performance curve depends on the diversity.

In the above discussed space-time block-coding techniques, the knowledge of perfect channel state information at the receiver seems to be highly unrealistic. This rationale has stimulated immense interest and debate regarding the importance of efficient channel estimator in the time-varying environment. The symbol-by-symbol channel path gain variations in the STBC block period and the channel estimation error due to Doppler spread are two unavoidable system performance degradation factors in the mobile wireless communication. Under such situations, the channel information may be derived by pilot symbol insertion and extraction (Cavers, 1991; Sampei and Sunaga, 1989). The receiver extracts the samples of training symbols periodically, and then interpolates them to estimate the fading channel. The detection of STBC over time-selective or fast fading channels has been studied (Tran and Sesay, 2002; Zheng and Burr, 2003), in which the channel is modeled as a first-order Markov process. The Kalman filtering algorithm is incorporated for tracking the time-selective flat fading channel (Liu et al., 2002). However, the computational complexity and requirement of the system model parameters may often preclude the Kalman filter based approaches. A time-varying channel is mainly estimated by the exponentially windowed recursive-least-squares (RLS) or the least-mean-squares (LMS) algorithms (Lin et al., 1995; Kohli and Mehra, 2006), which fail to track the channel variations effectively in the fast fading environment. However, a polynomial time-varying channel model technique (Borah and Hart, 1999) and the method to adaptively control the data window size with a variable forgetting factor (Lee et al., 1999) are two potential algorithms to improve the tracking ability.

Time-varying frequency-selective fading wireless channels can be modeled by using the tapped-delay-line filter, in which each channel tap-coefficient is considered to be an independent autoregressive process (Kohli and Mehra, 2008). The analytical and simulation results presented in Wang and Chang (1996) manifest that the first-order Markov channel provides a mathematically tractable model for the time-varying channels. Under such Rayleigh fading environment, the linear least squares algorithm (linear polynomial model-based approach (Borah and Hart, 1999) using variable forgetting factor (LSn-VFF) is developed for the channel estimation (Song et al., 2002). The lag error variance due to nonstationarity and the channel estimation error due to white Gaussian noise variance have a tradeoff relation with each other as far as the data window length is concerned. Therefore, the VFF is determined with the degree of nonstationarity and SNR by using the LMS algorithm. The LSn-VFF algorithm is reported to perform exceptionally well at high SNRs (Song et al., 2000). But, it increases the computational complexity.

Based on an extended estimation error criterion, which accounts for the nonstationarity of signal, a method for determining the numeric-variable-forgetting-factor (NVFF) is presented (Cho et al., 1991). When the signal experiences nonstationarity, the NVFF decreases automatically to estimate the global trend quickly using the extended estimation error criterion. On the contrary, NVFF increases under stationary conditions by increasing the memory for accurate estimation. Kohli et al. (2011) have presented a computationally efficient channel estimation method using LSn-NVFF algorithm combined with polynomial time-varying channel paradigm, which outperforms LSn-VFF and other higher-order polynomial based LS algorithms. In this correspondence, we propose the usage of LSn-NVFF algorithm based estimated complex channel coefficient matrix for the data symbol detection in the full transmission rate STBC wireless systems, which is expected to improve the BER performance of quasi-orthogonal STBCs even at the low SNRs in realistic wireless systems.

This paper is organized as follows. We first describe the proposed STBC system model working under the time-varying environment. Subsequently, details about the LSn-NVFF (first-order polynomial based approach) and LSn2-NVFF (second-order polynomial based approach) channel estimation algorithms were given. Further, the simulation results are presented to compare the BER performance of proposed system using different polynomial based variable forgetting factor LS algorithms. Finally, conclusions and future scope are given for the proposed STBC wireless systems with M-ary QAM signal constellations (Su and Xia, 2004).

STBC wireless communication system model

We consider a wireless system equipped with N transmit antennas and $M=1$ receive antenna to explore the transmit-diversity benefits. The received signal vector in the STBC system (as shown in Figure 1) can be modeled as

$$Y = CX + Z \tag{1}$$

where Y, the received signal vector, $Z = [\eta_1 \quad \eta_2]^T$ denotes the additive-white-Gaussian-noise (AWGN) sample vector with zero-mean and variance σ_η^2, X is the transmitted symbol signal vector with zero-mean, variance σ_x^2 and symbol duration T_s, and C is the channel coefficient matrix. The channel coefficients are assumed to be flat-fading time-varying, which follow the first-order autoregressive process because the realistic channel variations can be well approximated by using the first-order Markov process (Kohli, 2011). The first STBC from orthogonal design was proposed in Alamouti (1998) for the two-transmit antennas with rate 1, in which the transmitted symbol signal space-time 2×2 matrix is given by

$$X_{TXR}(2) = \begin{bmatrix} +A_1 & +B_1 \\ -\bar{B}_1 & +\bar{A}_1 \end{bmatrix} \tag{2}$$

where, $A_1 = x_1$, $B_1 = x_2$ and $\bar{A} = conjugate(A)$. Using Equation (1) and (2), it can be shown that

$$\hat{Y} = \begin{bmatrix} y_1 \\ y_2^* \end{bmatrix} = \begin{bmatrix} c_1 & c_2 \\ c_2^* & -c_1^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \eta_1 \\ \eta_2^* \end{bmatrix} \tag{3}$$

The channel coefficients are assumed to be constant for the period of $2T_s \; with \; P = 2$. To decode the actual transmitted symbol vector X from the processed received signal vector $\hat{Y}$, we form the decision vector $\hat{X}$ as

$$\hat{X} = [\hat{x}_1 \quad \hat{x}_2]^T = \hat{C}^H \hat{Y} = \hat{C}^H CX + \hat{C}^H Z \tag{4}$$

$$\tilde{X} = ML(\hat{X}) \tag{5}$$

where $(.)^T$, $(.)^H$, $ML(.)$ and $\tilde{X}$ are the simple transpose operator, the Hermitian transpose operator, the maximum likelihood operator and the finally detected symbol vector respectively. For the symbol decoding in Equation (4), we propose the usage of the estimated channel coefficient matrix $\hat{C}$. If the estimated channel approaches the actual channel conditions, that is, $\hat{C} \to C$, then only $(\hat{c}_2^* c_1 - \hat{c}_1 c_2^*) \to 0$, $(\hat{c}_1^* c_2 - c_1^* \hat{c}_2) \to 0$ and

$SNR \to \left[|c_1|^2 + |c_2|^2\right] \sigma_x^2 / \sigma_\eta^2$. Therefore, this two-branch transmitter diversity scheme with one receiver is equivalent to that of two-branch MRRC only under the perfect channel estimation conditions in the realistic wireless systems.

Further, the quasi-orthogonal space-time block-code (QSTBC) designs are proposed in (Jafarkhani, 2001), in which the requirement of the orthogonality in STBCs is relaxed to improve the transmission rate. For four transmitting antennas, the QSTBC with symbol rate 1 may be constructed from the scheme given in Alamouti (1998), in which the transmission symbol signal space-time 4×4 matrix is expressed as

$$X_{TXR}(4) = \left(\begin{array}{cc|cc} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ \hline -x_3^* & -x_4^* & x_1^* & x_2^* \\ x_4 & -x_3 & -x_2 & x_1 \end{array}\right) \tag{6}$$

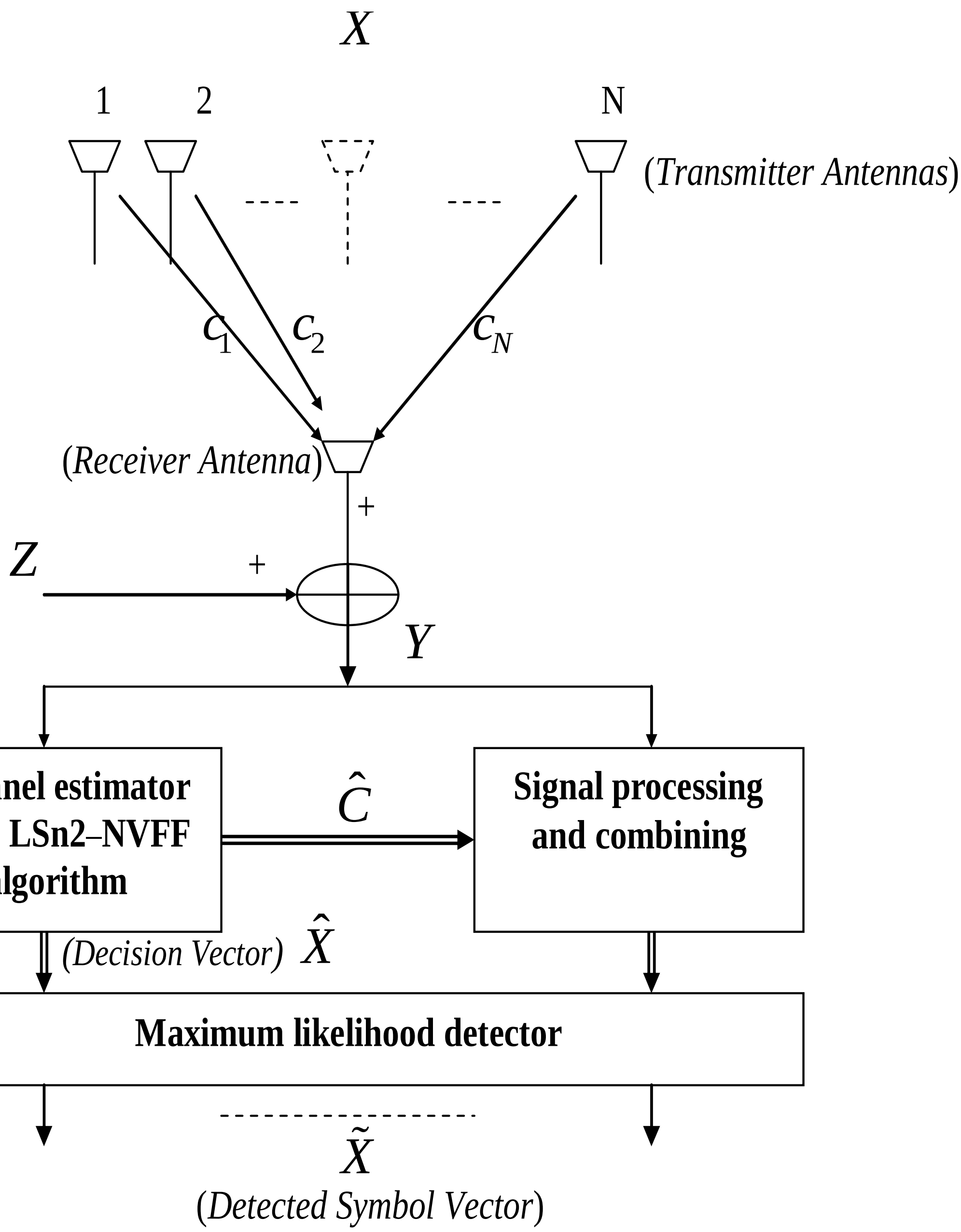

Figure 1. Proposed STBC system using higher-order polynomial based LS channel estimator.

$$X_{TXR}(4)=\left[\begin{array}{c:c} +A_2 & +B_2 \\ \hdashline -\bar{B}_2 & +\bar{A}_2 \end{array}\right] \tag{7}$$

where, $A_2 = X_{TXR}(2)$ with the symbol set $\{x_1, x_2\}$ and $B_2 = X_{TXR}(2)$ with the symbol set $\{x_3, x_4\}$, as depicted in Equation (6).

However, this QSTBC does not exhibit full diversity, which is sacrificed to boost rate of this QSTBC design. Here, the coefficients remain unchanged for the duration of $4T_s$ *with* $P = 4$. Subsequently, for eight transmitting antenna configuration, the QSTBC space-time 8×8 matrix with rate $3/4$ may be designed by using P_4, Q_4, S_4 *and* T_4 transmission symbol signal space-time 4×4 orthogonal matrices with rate $3/4$, which leads to

$$X_{TXR}(8)=\begin{pmatrix} x_1 & x_2 & x_3 & 0 & x_4 & x_5 & x_6 & 0 \\ -x_2^* & x_1^* & 0 & -x_3 & x_5^* & -x_4^* & 0 & x_6 \\ x_3^* & 0 & -x_1^* & -x_2 & -x_6^* & 0 & x_4^* & x_5 \\ 0 & -x_3^* & x_2^* & -x_1 & 0 & x_6^* & -x_5^* & x_4 \\ -x_4 & -x_5 & -x_6 & 0 & x_1 & x_2 & x_3 & 0 \\ -x_5^* & x_4^* & 0 & x_6 & -x_2^* & x_1^* & 0 & x_3 \\ x_6^* & 0 & -x_4^* & x_5 & x_3^* & 0 & -x_1^* & x_2 \\ 0 & x_6^* & -x_5^* & -x_4 & 0 & x_3^* & -x_2^* & -x_1 \end{pmatrix} \quad (8)$$

$$X_{TXR}(8)=\left[\begin{array}{c:c} P_4 & Q_4 \\ \hdashline R_4 & S_4 \end{array}\right] \quad (9)$$

In this case, the time-varying flat-fading channel is not time-selective in nature, therefore the channel coefficients vary after a period of $8T_s \; with \; P=8$.

Channel estimator using LSn2–NVFF adaptive algorithm

Signal reception under realistic wireless environment

Let the received pilot signal be

$$y_{Pilot}(n)=c_{Pilot}^H(n)\,x_{Pilot}(n)+\eta_{Pilot}(n) \quad (10)$$

where, $x_{Pilot}(n)$ is the transmitted pilot symbol signal with zero-mean and unity variance, $\eta_{Pilot}(n)$ is the zero-mean AWGN with variance σ_η^2, and

$$c_{Pilot}(n)=\alpha c_{Pilot}(n-1)+q_{Pilot}(n) \quad (11)$$

which is the time-varying channel-coefficient. Each channel-coefficient $c_{Pilot}(n)$ is an independent stationary ergodic first-order Markov process with the correlation-coefficient $\alpha=J_0\{2\pi f_d(PT_s)\}$ and with the zero-mean process-noise variance σ_q^2, which is an approximation of the realistic wireless communication channel following Rayleigh probability density function for the multipath fading (Wang and Chang, 1996); where f_d is the maximum Doppler frequency, and $J_0(.)$ is the Bessel function of first-kind and zeroth-order. The channel-coefficient is assumed to change after every P time-slots used to transmit STBC data symbols. Using estimated channel-coefficient $w(n)$, the estimated received signal is

$$\hat{y}_{Pilot}(n)=w^H(n)\,x_{Pilot}(n) \quad (12)$$

Here, the estimation error is $e_{Pilot}(n)=y_{Pilot}(n)-\hat{y}_{Pilot}(n)$ with zero-mean and variance σ_e^2. Using Equations (10) to (12), it may be proved that the estimation error variance is

$$\sigma_e^2=\sigma_\eta^2\left(1+\sigma_q^2/\sigma_\eta^2\right) \quad (13)$$

for approximation $w(n)\approx\alpha c_{Pilot}(n-1)$

$$\sigma_e^2\approx\sigma_\eta^2 \text{ for approximation } \sigma_q^2/\sigma_\eta^2<<1 \quad (14)$$

Channel estimation using polynomial paradigm

Under such Rayleigh fading environment, the linear least squares algorithm (linear polynomial model-based approach) using variable forgetting factor (LSn-VFF) exhibits "the lag error variance due to time variations and AWGN variance in channel estimation error" in a tradeoff relation with each other, which performs well only at high SNRs (Song et al., 2002) at the cost of increased computational complexity. Based on an extended estimation error criterion, which accounts for the nonstationarity of signal, the numeric variable forgetting factor based LSn2-NVFF algorithm is presented (Kohli et al., 2011). By invoking Taylor's theorem, the time-variations of the pilot channel-coefficient is explicitly represented in terms of the polynomial paradigm. It results in

$$c_{Pilot}(n)=c_{Pilot0}(n)+\frac{n}{1!}c_{Pilot1}(n)+\frac{n^2}{2!}c_{Pilot2}(n)+..... \quad (15)$$

where, $c_{Pilot0}, c_{Pilot1}, c_{Pilot2}, ...$ are the time-variation parameters for the channel-coefficient $c_{Pilot}(n)$. The LSn2 estimation algorithm utilizes the second-order channel model (15) by considering the adaptive weight $w(n)=w_0(n)+nw_1(n)+\frac{n^2}{2}w_2(n)$, which is a modification of LSn algorithm presented in Song et al. (2002). Further, the tracking capability of LSn2 algorithm can be improved by the incorporation of variable forgetting factor (VFF) using LMS adaptation algorithm (Song et al., 2002) and numeric variable forgetting factor (NVFF) (Kohli et al., 2011) without the explicit knowledge of the process noise variance. The LSn2-NVFF algorithm uses forgetting factor

$\lambda(n)$ to update the channel state after (PT_s) symbol duration. The channel estimation procedure is as follows

$$\mathbf{X}(n) = [x_{Pilot}(n)\ nx_{Pilot}(n)\ \frac{n^2}{2}x_{Pilot}(n)]^T \quad (16)$$

$$\mathbf{W}(n-1) = [w_0^H(n-1)\ w_1^H(n-1)\ w_2^H(n-1)]^H \quad (17)$$

$$\varepsilon(n) = y(n) - \mathbf{W}^H(n-1)\mathbf{X}(n) \quad (18)$$

$$\mathbf{k}(n) = \frac{\mathbf{P}(n-1)\mathbf{X}(n)}{\lambda(n)\sigma_\eta^2 + \mathbf{X}^H(n)\mathbf{P}(n-1)\mathbf{X}(n)} \quad (19)$$

$$\mathbf{W}(n) = \mathbf{W}(n-1) + \mathbf{k}(n)\varepsilon(n)^* \quad (20)$$

$$\mathbf{P}(n) = \frac{1}{\lambda(n)}[\mathbf{P}(n-1) - \mathbf{k}(n)\mathbf{X}^H(n)\mathbf{P}(n-1)] \quad (21)$$

The minimum mean square error (MMSE) in channel estimation is $J = E[|c_{Pilot}(n) - w(n)|^2]$. The Equations (16) to (21) are used in combination with NVFF to develop LSn2-NVFF algorithm. The speed of adaptation is proportional to the asymptotic memory length $N = (1-\lambda)^{-1}$ (Cho et al., 1991). The memories corresponding to $\lambda_{\max}$ and $\lambda_{\min}$ are denoted by $N_{\max}$ and $N_{\min}$ respectively. If process noise variance is small in comparison to the variance of AWGN, that is, $\sigma_q^2 << \sigma_\eta^2$, then $\sigma_e^2 \approx \sigma_\eta^2$ and the extended estimation error may be determined by

$$Z(n) = \frac{1}{M}\sum_{m=0}^{M-1}\left|e(n-m)\right|^2 \quad (22)$$

To ensure that the averaging in the aforementioned equation is not obscuring, the nonstationarity introduced by time-varying channel, the value of M is kept smaller than minimum asymptotic memory length ($M << N_{\min}$). The NVFF is determined by using the extended estimation error in Equation (22), such that

$$N(n) = \frac{\sigma_e^2 N_{\max}}{Z(n)} \approx \frac{\sigma_\eta^2 N_{\max}}{Z(n)} \quad (23)$$

$$\lambda(n) = 1 - (N(n))^{-1} \quad (24)$$

Under stationary conditions, it takes relatively long time for accurate parameter estimation for a value of NVFF close to unity (Cho et al., 1991); in which, $N_{\max}$ controls the speed of adaptation. On the contrary, a small value of NVFF appears beneficial under nonstationary environment, which is bounded (lower) by $\lambda(n) \geq \lambda_{\min}$ to guarantee positive non-zero values of NVFF.

SIMULATION RESULTS

For simulations, the BPSK, 4-QAM and 8-QAM signal constellations mentioned in Su and Xia (2004) are considered as digital modulation techniques in the proposed STBC wireless communication system. The presented results are based on the ensemble average of 250 independent simulation runs. Note that we have kept $\sigma_q^2 = 0.001$, $\sigma_\eta^2 = 0.01$ and $M = 3$. The pilot channel tracking is performed for LSn2-VFF (Appendix) and LSn-VFF algorithms with $f_d(PT_s) = 0.001$; where $\lambda_{\max}$, $\lambda_{\min}$ and step-size μ are empirically chosen as 0.99, 0.75 and 0.005 respectively for all cases. The tracking performance results presented in Kohli et al. (2011) depict that LSn2 algorithm (with second-order channel model) combats lag noise more efficiently than LSn algorithm, but at the cost of increased computational complexity. Subsequently, it is apparent from the simulation results shown in Kohli et al. (2011) that LSn-VFF and LSn-NVFF algorithms supersede LSn2-VFF and LSn2-NVFF algorithms under time-varying environment. Both variable forgetting factors overwhelm the loss in tracking capability caused due to the first-order channel model. The simulation results are in good agreement with previous studies (Song et al., 2002). For smoothly fading channels, the LSn-NVFF algorithm reduces tracking weight error relatively more as compared to LSn-VFF algorithm. At fading rate $f_d(PT_s) = 0.01$, the tracking performances of both adaptive algorithms are observed to be approximately equal.

For the bit-error-rate (BER) performance evaluation of the proposed STBC communication system, the time-varying wireless fading channels with fading rate $f_d(PT_s) \leq 0.01$ are considered for the simulations. For full transmission rate and full spatial diversity (2×2) orthogonal STBC wireless system (2), it may be inferred from Figure 2 that at the lower values of SNRs, $BER_{LSn-NVFF} < BER_{LSn2-NVFF} < BER_{LSn-VFF} < BER_{LSn2-VFF}$ and at the higher values of SNRs, $BER_{LSn-NVFF} \leq BER_{LSn-VFF} < BER_{LSn2-VFF} < BER_{LSn2-NVFF}$.

Similarly for the full transmission rate and partial spatial diversity (4×4) quasi-orthogonal STBC wireless system (6), it is apparent from Figure 3 that at the lower values of SNRs, $BER_{LSn-NVFF} < BER_{LSn2-NVFF} < BER_{LSn-VFF} < BER_{LSn2-VFF}$ and at the higher values of SNRs, $BER_{LSn-VFF} \leq BER_{LSn-NVFF} < BER_{LSn2-VFF} < BER_{LSn2-NVFF}$.

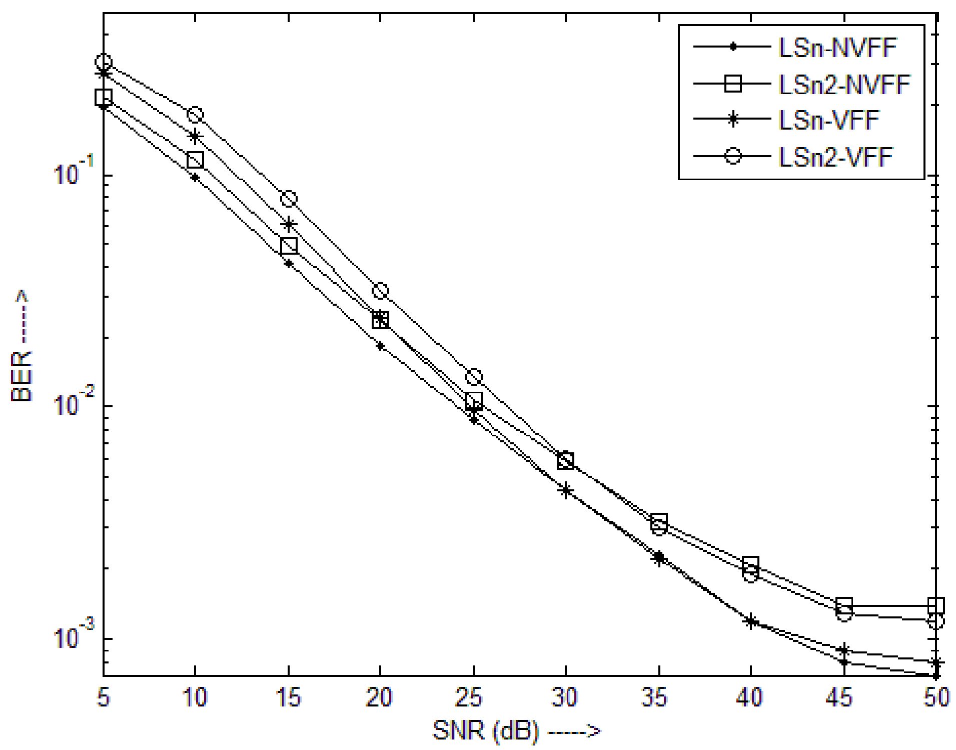

Figure 2. BER performance vs. SNR (dB) for the proposed orthogonal (2×2) STBC wireless system.

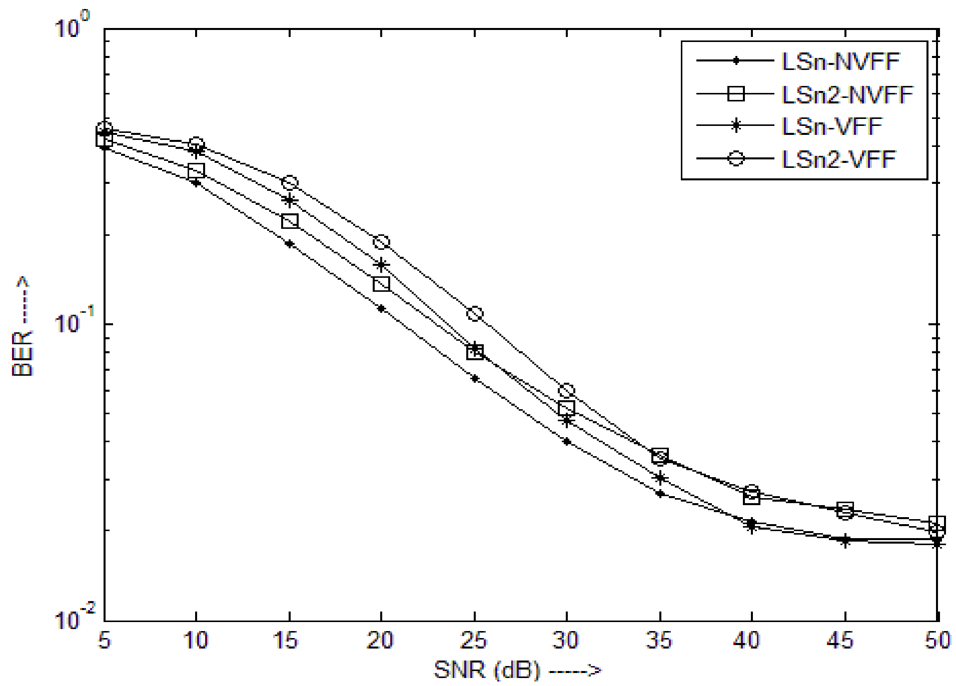

Figure 3. BER performance vs. SNR (dB) for the proposed quasi-orthogonal (4×4) STBC wireless system.

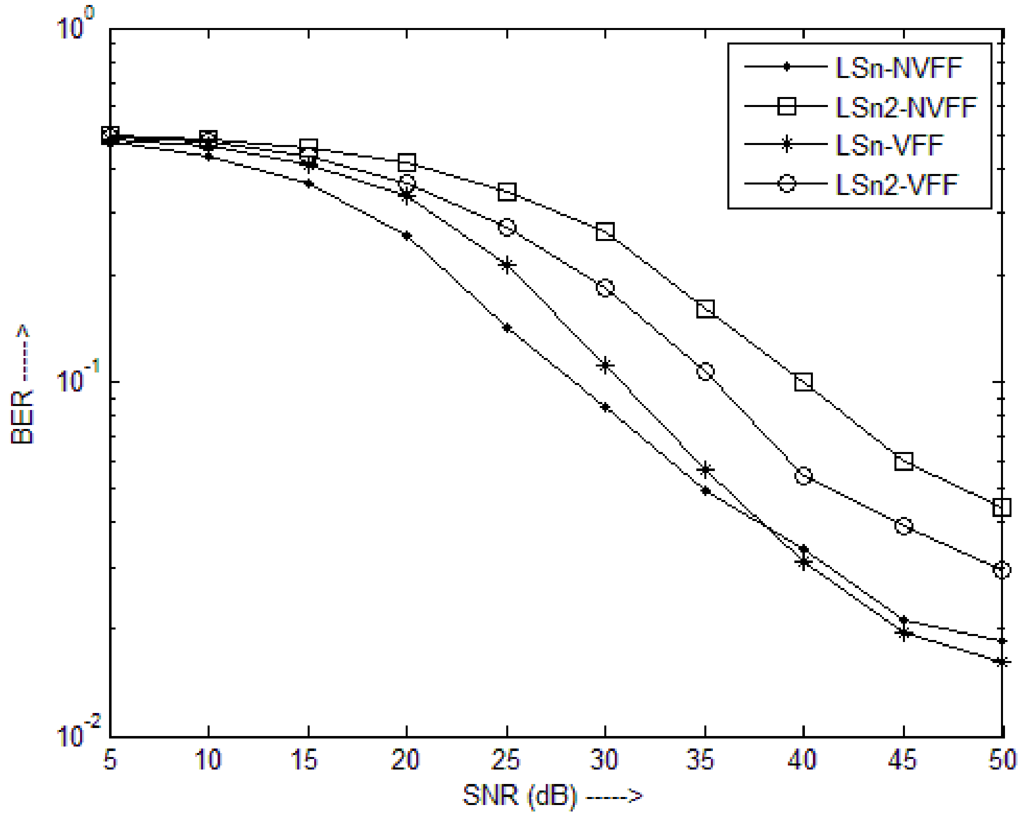

Figure 4. BER performance vs. SNR (dB) for the proposed quasi-orthogonal (8×8) STBC wireless system.

These STBC systems with LSn-NVFF algorithm based channel estimator outperform the higher-order as well as the LMS algorithm based system configurations.

However for the $3/4$ transmission rate and the partial spatial diversity (8×8) quasi-orthogonal STBC wireless system (8), the simulation results presented in Figure 4 depict that at the lower values of SNRs, $BER_{LSn-NVFF} < BER_{LSn-VFF} < BER_{LSn2-VFF} < BER_{LSn2-NVFF}$ and at the higher values of SNRs $BER_{LSn-VFF} \le BER_{LSn-NVFF} < BER_{LSn2-VFF} < BER_{LSn2-NVFF}$.

At high SNRs, the tracking performance of LSn-VFF algorithm is found to be exceptionally well, which improves the BER performance of the proposed system under less noisy environment. However, the overall simulation results indicating BER performance evidence that the LSn-NVFF algorithm based communication systems supersede LSn2-NVFF algorithm based approaches. Moreover, the BER performance of all the proposed configurations degrades due to the loss of spatial diversity gain in case of the usage of quasi-orthogonal STBCs.

CONCLUDING REMARKS AND FUTURE SCOPE

The presented STBC wireless system using LSn-NVFF algorithm based channel estimator not only performs better than LSn-VFF and LSn2-VFF algorithm based configurations, but also precludes the need of LMS algorithm in variable forgetting factor updating at each iteration. Moreover, the usage of NVFF reduces the computational burden. It is apparent from the simulation results that the proposed STBC communication system using the higher-order polynomial model-based LS algorithms ($e.g.$, LSn2) in conjunction with NVFF are not providing any additional advantage in the BER performance improvement. However, the linear least squares algorithm using NVFF is found to be efficient under slow and smoothly time-varying fading channels, which in turn improves the BER performance of the STBC wireless communication systems with M-ary QAM techniques. Future work includes the BER performance evaluation of high $R_{STBC} = K/P$ (transmission rate) STBC systems with proposed channel estimation techniques, while using different M-ary QAM configurations.

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APPENDIX

For unknown process noise variance σ_q^2 and known AWGN variance σ_η^2 at the receiver with LSn2-VFF algorithm based channel estimator, the computationally complex VFF is updated as

$$\lambda(n) = \left\{ \lambda(n-1) + \frac{\mu}{\sigma_\eta^2} \mathrm{Re}[\mathbf{D}^H(n-1)\mathbf{X}(n)\varepsilon(n)^*] \right\}_{\lambda_{\min}}^{\lambda_{\max}} \quad \text{(A1)}$$

$$\mathbf{D}(n) = [\mathbf{I} - \mathbf{k}(n)\mathbf{X}^H(n)]\mathbf{D}(n-1) + \mathbf{M}(n)\mathbf{X}(n)\frac{\varepsilon(n)^*}{\sigma_\eta^2} \quad \text{(A2)}$$

$$\mathbf{M}(n) = \lambda(n)^{-1}[\mathbf{I} - \mathbf{k}(n)\mathbf{X}^H(n)]\mathbf{M}(n-1)[\mathbf{I} - \mathbf{X}(n)\mathbf{k}^H(n)] + \left(\lambda(n)\sigma_\eta^{-2}\right)^{-1}\mathbf{k}(n)\mathbf{k}^H(n) - \lambda(n)^{-1}\mathbf{P}(n) \quad \text{(A3)}$$

where μ is the step-size (Kohli and Mehra, 2006), which controls convergence, tracking characteristics and stability of the LMS algorithm in (A1). The variation range for VFF is $[\lambda_{\min}, \lambda_{\max}]$ to ensure the bounded non-negative value of VFF.