A Layered-Steered Space-Time Coded System with Optimal Power Allocation

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Abstract*—Layered Steered Space-Time Codes (LSSTC) is a recently proposed multiple-input multiple-output (MIMO) system that combines the benefits of vertical Bell Labs space-time (VBLAST) scheme, space-time block codes (STBC) and beamforming. We suggest a new downlink scheme employing LSSTC with optimal power allocation, by assuming that the user feeds the BS with the average SNR per VBLAST layer through the uplink feedback channel. The motivation behind proposing such a system is to enhance the error performance by assigning power to the layers in an optimum manner. We refer to the system proposed as the optimum power allocation LSSTC (OPA-LSSTC). We will show that the OPA-LSSTC can provide about a 3 dB gain compared to the equal power allocation case.

I. INTRODUCTION

Various techniques have been proposed to counter the problem of propagation conditions, and to achieve data rates that are very close to the Shannon limit. One of these techniques is using MIMO systems which uses antenna arrays at both the transmitter and the receiver. Wolniansky $et\ al.$ has proposed in [1] the well-known MIMO scheme, known as VBLAST. In VBLAST architecture, parallel data streams are sent via the transmit antennas at the same carrier frequency. Given that the number of receive antennas is greater than or equal to the number of transmit antennas, the receiver employs a low complexity method based on successive interference cancellation (SIC) to detect the transmitted data streams. In this manner, VBLAST can achieve high spectral efficiencies without any need for increasing the system's bandwidth or transmitted power.

While MIMO systems as VBLAST can improve the system capacity greatly [2], it is difficult to implement antenna arrays on hand-held terminals due to size, cost and hardware limitation [3], also it has poor energy performance and doesnt fully exploit the available diversity. In order to overcome these problems, Alamouti has presented in [3] a new scheme called STBC with two transmit and one receive antennas that provides the same diversity order as maximal-ratio receiver combining (MRRC) with one transmit and two receive antennas. With the tempting advantages of VBLAST and STBC, many researchers have attempted to combine these two schemes to result in a multilayered architecture called MLSTBC [4] with each layer being composed of antennas that corresponds to a specific STBC. This combined scheme arises as a solution to jointly achieve spatial multiplexing and diversity gains simultaneously. With MLSTBC scheme, it is possible to increase the data rate while keeping a satisfactory link quality in terms of symbol error rate (SER) [5].

In [6] beamforming was combined with MLSTBC to produce a hybrid system called the layered steered space time codes (LSSTC). The addition of beamforming to MLSTBC further improves the performance of the system by focusing the energy towards one direction, where the antenna gain is increased in the direction of the desired user, while reducing the gain towards the interfering users.

The main contribution of this paper is finding the optimum power allocation at the transmitter side in order to minimize the probability of error. Our analysis is based on the results of [7] for VBLAST applying the power allocation scheme and extends to the LSSTC case where beamforming and STBC are involved. We refer to the system proposed in this chapter as the power allocation LSSTC (PA-LSSTC). We also investigate the performance of PA-LSSTC, and extend the results to M-ary PSK and M-ary QAM. The remainder of this paper is organized as follows. Section II presents the system model. Section III presents the notation used for the power allocation scheme. Section IV shows the performance analysis of PA-LSSTC, in which we derive a formula for the probability of error of the individual layers employing different modulation schemes. Furthermore, we formulate the average SER of the PA-LSSTC system. In Section V, the optimum PA scheme for LSSTC is derived so that the probability of error is minimized. Section VI discusses the complexity of the proposed system. Numerical results are presented in Section VII, followed by our conclusions.

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II. System Model

Figure 1 shows the block diagram of an OPA-LSSTC system, the system has N_T total transmitting antennas and N_R receiving antennas and is denoted by an (N_T, N_R) system. The antenna architecture employed in Figure 1 has M transmit adaptive antenna arrays (AAs) spaced sufficiently far apart in order to experience independent fading and hence achieve transmit diversity. Each of the AAs consists of L elements that are spaced at a distance of $\lambda/2$ to ensure achieving beamforming. A block of B input information bits is sent to

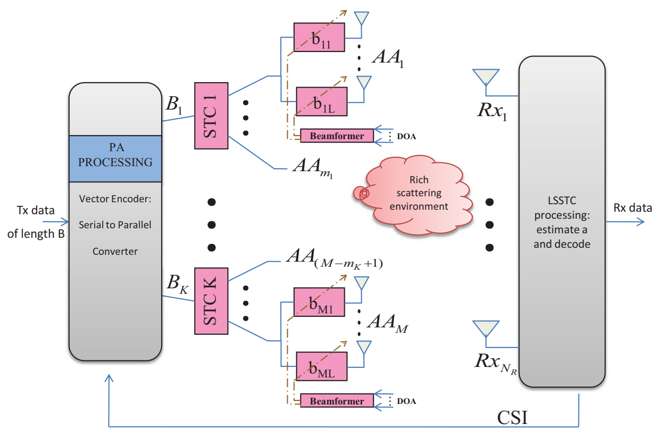

Fig. 1. Block diagram of a single user LSSTC system.

the vector encoder of LSSTC and serial-to-parallel converted to produce K streams (layers) of length $B_1, B_2, \ldots, B_K$, where $B_1 + B_2 + \cdots + B_K = B$. Each group of B_k bits, $k \in [1, K]$, is then encoded by a component space-time code STC_k associated with m_k transmit AAs, where $m_1 + m_2 + \cdots + m_K = M$. The output of the k^{th} STC encoder is a $m_K \times l$ codeword, $\mathbf{c}_i$, that is sent over l time intervals. The space-time coded symbols from all layers can be written as $\mathbf{C} = [\mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_K]^T$, where $\mathbf{C}$ is an $M \times l$ matrix.

The coded symbols from $\mathbf{C}$ are then processed by the corresponding beamformers, and then transmitted simultaneously over the wireless channels. For proper operation, N_R should be at least equal to K. The BS of OPA-LSSTC prompts the user to feedback the CSI per layer via the feedback channel along with the direction of arrival (DOA) data. Also the transmitter is capable of performing OPA processing.

III. The Power Allocation Scheme

The PA pattern for the PA-LSSTC scheme is defined in a similar manner as for VBLAST in [7]. The system is characterized by the layer PA pattern vector as $\mathbf{K}_L = [K_{L,1}, K_{L,2}, \cdots, K_{L,K-1}]$ where K is the number of layers, and $K_{L,i}$ is defined as the transmit power ratio of the i^{th} layer to the sum of power of layers $i+1, \cdots, K$. $K_{L,i}$ is defined by

$$K_{L,i} = \frac{P_{L,i}}{\sum_{j=i+1}^{K} P_{L,j}}, \quad i = 1, 2, \cdots, K-1, \tag{1}$$

where $P_{L,i}$ denotes the transmit power of the i^{th} layer. For fair comparison among different energy allocation patterns, P_i must satisfy the energy conservation constraint, $P_T = \sum_{i=1}^{M} P_i = P_s$, where P_s denotes the average transmit power per modulation symbol.

IV. Performance Analysis

In this section, the performance of LSSTC systems employing PA scheme is analyzed. The receiver is assumed to have a fixed detection ordering and uses serial group interference cancellation (SGIC) for detection. The analysis is carried out for slow Rayleigh fading channels, in which we assume that the channel remains constant for many STBC blocks. Thus the transmitter obtains the estimates of the average SNR per layer from the receiver, finds the optimum power allocation, and uses the same power allocation pattern till the channel changes. Using this assumption minimizes the feedback load by a significant amount. We first denote the SER of the i^{th} sub-stream under PA pattern $\mathbf{K}_L$ and noise of variance N_0 as $P_{e_i|(\mathbf{K}_L, N_0)} = P\{\hat{s}_i \neq s_i \mid \mathbf{K}_L, N_0\}$. The SER of the i^{th} layer has the form

$$P_{e_i|(\mathbf{K}_L, N_0)} = \sum_{l=0}^{i-1} P\{s_i \neq \hat{s}_i, A_{i-1}^{l} \mid \mathbf{K}_L, N_0\}, \tag{2}$$

where A_{i-1}^{l} defines the event of having l errors in the symbols $\hat{s}_1 \sim \hat{s}_{i-1}$. Let V_m denote one of the $\binom{i-1}{l}$ events which has detection errors at certain l layers among the $i-1$ processed layers at each time slot. Thus V_m is a set that contains the layer indices for one of the $\binom{i-1}{l}$ combinations of choosing l error symbols among the $i-1$ layers [7], where $m = 1, 2, \cdots, \binom{i-1}{l}$. We can express V_m as a set $V_m = \{v_{m,1}, v_{m,2}, \cdots, v_{m,l}\}$ where $v_{m,k}$ denotes the index of the layer in which the k^{th} error has occurred. For instance, if $V_m = \{1, 3, 4\}$ then the first error was in the first layer, while the second was in the third layer, and the third was in the fourth layer. Also, we assume that $v_{m,1} < v_{m,2} < \cdots < v_{m,l}$, $v_{m,k} \in \{1, 2, \cdots, i-1\}$. Further more, the complement set of V_m is defined as

$$W_m = \{1, 2, \cdots, i-1\} - V_m = \{w_{m,1}, w_{m,2}, \cdots, w_{m,i-1-l}\}$$

where $w_{m,1} < w_{m,2} < \cdots < w_{m,i-1-l}$, $w_{m,k} \in \{1, 2, \cdots, i-1\}$. Similar to [7] we define $e_{V_m}^{i}$ as the event of having the i^{th} layer in error and having l erroneous layers indicated by V_m given a specific PA pattern $\mathbf{K}_L$ and noise of variance N_0

$$e_{V_m}^{i} = \Big\{ s_i \neq \hat{s}_i \bigcap_{\forall v_{m,k} \in V_m} \{s_{v_{m,k}} \neq \hat{s}_{v_{m,k}}\} \bigcap_{\forall w_{m,k} \in W_m} \{s_{w_{m,k}} = \hat{s}_{w_{m,k}}\} \mid \mathbf{K}_L, N_0 \Big\}. \tag{3}$$

Then, the probability that the i^{th} layer along with l proceeding layers defined by V_m given $\mathbf{K}_L$ and N_0 can be found by simply summing the probability of all the possible combinations of V_m. Mathematically, we can write this as

$$P\{s_i \neq \hat{s}_i, A_{i-1}^l \mid \mathbf{K}_L, N_0\} = \sum_{m=1}^{\binom{i-1}{l}} P(e_{V_m}^i). \quad (4)$$

Moreover, $P(e_{V_m}^i)$ can be decomposed into a product of i components as follows

$$P(e_{V_m}^i) = P(e_{V_m}^{i,i}) \cdot P(e_{V_m}^{i,i-1}) \cdots P(e_{V_m}^{i,1}) = \prod_{t=1}^{i} P(e_{V_m}^{i,t}), \quad (5)$$

where $e_{V_m}^{i,t}$ is defined similar to $e_{V_m}^i$ except that it corresponds to the t^{th} layer (whether erroneous or correct). In [7], $e_{V_m}^{i,t}$ was defined as

$$e_{V_m}^{i,t} = \begin{cases} \Big\{ s_t \neq \hat{s}_t \mid \bigcap_{\forall v_{m,k} < t} \{s_{v_{m,k}} \neq \hat{s}_{v_{m,k}}\} \\ \quad \bigcap_{\forall w_{m,k} < t} \{s_{w_{m,k}} = \hat{s}_{w_{m,k}}\}, \mathbf{K}_L, N_0 \Big\}, \quad t \in V_m \\ \Big\{ s_t = \hat{s}_t \mid \bigcap_{\forall v_{m,k} < t} \{s_{v_{m,k}} \neq \hat{s}_{v_{m,k}}\} \\ \quad \bigcap_{\forall w_{m,k} < t} \{s_{w_{m,k}} = \hat{s}_{w_{m,k}}\}, \mathbf{K}_L, N_0 \Big\}, \quad t \in W_m \end{cases} \quad (6)$$

Thus, using (5) in (4) the latter becomes

$$P\{s_i \neq \hat{s}_i, A_{i-1}^l \mid \mathbf{K}_L, N_0\} = \sum_{m=1}^{\binom{i-1}{l}} \prod_{t=1}^{i} P(e_{V_m}^{i,t}). \quad (7)$$

The exact SER of the t^{th} layer without error propagation given the diversity order and the SNR for different modulation schemes have been derived in the literature [8]. We denote the SER of t^{th} layer as $P_e(D_t, \rho_t)$, where D_t and ρ_t are the diversity order and the SNR of the t^{th} layer, respectively. By approximating the symbol errors caused in the previous layers as Gaussian random variable, we can write the following

$$P(e_{V_m}^{i,t}) = \begin{cases} P_e(m_t(N_R - K + t), P_t/\sigma_t^2), & t \in V_m \\ 1 - P_e(m_t(N_R - K + t), P_t/\sigma_t^2), & t \in W_m, \end{cases} \quad (8)$$

where σ_t^2 is the variance of the approximated Gaussian noise variable. The value of σ_t^2 depends on the modulation scheme and the symbol energy used in previous layers as will be described in the following subsections.

A. BPSK

The diversity order of the sub-streams of the i^{th} layer is $D_i = m_i(N_R - K + i)$. According to [8], the exact SER of the i^{th} layer without error propagation using BPSK modulation,

$$P_e(D_i, \rho_i) = \left[\frac{1}{2}(1-\mu_i)\right]^{D_i} \sum_{\tau=0}^{D_i - 1} \binom{D_i - 1 + \tau}{\tau} \left[\frac{1}{2}(1+\mu_i)\right]^{\tau}, \quad (9)$$

where $\mu_i = \sqrt{\rho_i/(1+\rho_i)}$ and ρ_i denotes the SNR of the i^{th} layer. By applying Gaussian approximation to the error propagation component, and extending the results of [7] for LSSTC, the noise variance, σ_t^2 , can be approximated by

$$\begin{aligned} \sigma_t^2 &= N_0 + \sum_{\forall v_{m,k} < t} \mathrm{E}\left[\|\mathbf{h}_{v_{m,k}}\|^2\right] \cdot \mathrm{Var}\left[e_{v_{m,k}} \mid x_{v_{m,k}} \neq \hat{x}_{v_{m,k}}\right] \\ &= N_0 + \sum_{\forall v_{m,k} < t} L^2 \cdot 4P_{L,v_{m,k}} \\ &= N_0 + 4L^2 \cdot \sum_{\forall v_{m,k} < t} P_{L,v_{m,k}}, \end{aligned} \quad (10)$$

where $\|\mathbf{h}_{v_{m,k}}\|^2$, $P_{L,v_{m,k}}$, and $e_{v_{m,k}}$ denotes the Frobenius norm (FN), transmit power, and the error event of layer $v_{m,k}$ respectively. $E[.]$ is the expectation operator, and $Var[.]$ is the variance operator.

B. M-QAM

We consider square M-QAM modulation schemes such as 16-QAM, 64-QAM, etc. Under a Rayleigh fading channel and with diversity order D_i, the SER of a square M-QAM can be written as follows [9]

$$P_e(D_i, \rho_i) = 4\left(1 - \frac{1}{\sqrt{M}}\right) I_1 - 4\left(1 - \frac{1}{\sqrt{M}}\right)^2 I_2, \quad (11)$$

where the terms I_1 and I_2 are defined as

$$I_1 = \left[\frac{1}{2}(1-\mu_i)\right]^{D_i} \cdot \sum_{k=0}^{D_i - 1} \binom{D_i - 1 + k}{k} \left[\frac{1}{2}(1+\mu_i)\right]^{k}, \quad (12)$$

$$\begin{aligned} I_2 &= \frac{1}{4} - \mu_i \cdot \left(\frac{1}{2} - \frac{1}{\pi} \cdot \tan^{-1}(\mu_i)\right) \cdot \sum_{k=0}^{D_i - 1} \binom{2k}{k} \cdot (4\tau_i)^{-k} \\ &+ \frac{\mu_i}{\pi} \sin\left(\tan^{-1}(\mu_i)\right) \\ &\cdot \sum_{k=1}^{D_i - 1} \sum_{i=1}^{k} \tau_i^{-k} \cdot T_{ik} \cdot \left(\cos\left(\tan^{-1}(\mu_i)\right)\right)^{2(k-i)+1}, \end{aligned} \quad (13)$$

where

$$\mu_i \triangleq \sqrt{\frac{\rho_i}{\frac{2}{3}(M-1) + \rho_i}}, \quad (14)$$

$$\tau_i \triangleq \left(\frac{3\rho_i}{2(M-1)} + 1\right), \quad (15)$$

$$T_{ik} \triangleq \frac{\binom{2k}{k}}{\binom{2(k-i)}{k-i} 4^i \cdot (2(k-i)+1)}. \quad (16)$$

The variance of the effective noise affecting the t^{th} layer is approximated by

$$\sigma_t^2 = N_0 + \frac{6L^2}{M-1} \cdot \sum_{\forall v_{m,k} < t} P_{L,v_{m,k}}. \quad (17)$$

C. M-PSK

Using the result of [9], the SER of i^{th} layer assuming perfect interference cancellation and M-PSK modulation with diversity order D_i and layer SNR ρ_i is written as follows

$$P_e(D_i,\rho_i) = \frac{M-1}{M} - \frac{\mu_i}{\sqrt{\mu_i^2+1}}\left(\frac{1}{2}+\frac{\omega_i}{\pi}\right)\sum_{k=0}^{D_i-1}\binom{2k}{k}\left[4(\mu_i^2+1)\right]^{-k} - \frac{\mu_i}{\sqrt{\mu_i^2+1}}\cdot\frac{1}{\pi}\sin(\omega_i)\sum_{k=1}^{D_i-1}\sum_{i=1}^{k}\frac{T_{ik}}{(\mu_i^2+1)^k}\left[\cos(\omega_i)\right]^{2(k-i)+1} \quad (18)$$

where

$$\mu_i \triangleq \sqrt{\rho_i}\sin(\frac{\pi}{M}), \quad (19)$$

$$\omega_i \triangleq \tan^{-1}\left(\frac{\sqrt{\rho_i}\cos(\frac{\pi}{M})}{\sqrt{\mu_i^2+1}}\right), \quad (20)$$

$$T_{ik} \triangleq \frac{\binom{2k}{k}}{\binom{2(k-i)}{k-i}4^i\cdot(2(k-i)+1)}. \quad (21)$$

The variance of the effective noise affecting the t^{th} layer is approximated by [7] as

$$\begin{aligned}\sigma_t^2 &= N_0 + \sum_{\forall v_{m,k}<t} \mathrm{E}\left[\|\mathbf{h}_{v_{m,k}}\|^2\right]\cdot \mathrm{Var}\left[e_{v_{m,k}} \mid x_{v_{m,k}} \neq \hat{x}_{v_{m,k}}\right] \\ &= N_0 + \sum_{\forall v_{m,k}<t} L^2\cdot 4\cdot\sin^2\left(\frac{\pi}{M}\right)P_{L,v_{m,k}} \\ &= N_0 + 4L^2\cdot\sin^2\left(\frac{\pi}{M}\right)\cdot\sum_{\forall v_{m,k}<t} P_{L,v_{m,k}}. \end{aligned} \quad (22)$$

After finding the expressions of σ_t^2 and $P_e(D_i,\rho_i)$, they can be substituted into (8). The SER of the i^{th} layer, $P_{e_i|(\mathbf{K}_L,N_0)}$, can be evaluated by combining (2), (7), and (8).

V. Optimum Power Allocation

In this Section, we aim to find the optimum power allocation $\mathbf{K}$ that would result in optimizing the performance by minimizing the probability of error for the LSSTC system. To achieve this we need to differentiate the formula of the average SER $P_{av|(\mathbf{K}_L,N_0)}$ with respect to $\mathbf{K}_L$ to find the minimum value of the SER. Clearly such analytical differentiation is very difficult, therefore we use a numerical approach applying Newton's method [7]. To minimize $P_{av|(\mathbf{K}_L,N_0)}$, we need to find the value of $\mathbf{K}_L = [K_{L,1}, K_{L,2}, \cdots, K_{L,K-1}]$ that satisfies the following set of equations

$$\frac{\partial P_{av|(\mathbf{K}_L,N_0)}}{\partial K_{L,i}} = 0, \quad i = 1,2,\cdots,K-1. \quad (23)$$

To solve the set of equations in (23) by Newton's method, we start with an initial guess. The optimum PA pattern $\mathbf{K}_{opt}$ can be obtained by repeating Newton's method until it converges, which depends on the initial guess and the step size.

Throughout this paper, the following notation will be used:

- EPA-LSSTC will be used to denote equal power allocation LSSTC system in which all the layers are assigned the same amount of power.
- OPA-LSSTC will be used to denote optimum power allocation LSSTC system in which the layers are assigned different amounts of power according to $\mathbf{K}_{opt}$.

VI. Complexity of OPA-LSSTC

It was observed that the optimum power allocation at high SNR provides a significant SNR gain with little increase in the complexity of the system. The main parameters that will be affected by the OPA processing are the feedback load and the number of operations per unit time.

The BS analyzes the CSI data to optimize the performance by assigning the layer powers according to $\mathbf{K}_{opt}$. As a result, the number of operations will increase, and faster processors will be required. Observing the simulation results, the computational complexity was noted to be higher for small SNR values. The reason for that is hardware limitation, as the tiny difference between the optimum powers will require the step size δ to be very small. In such a case, finding the solution by numerical methods will require a huge number of operations. The minimum step size used to solve the optimum PA equations was 10^{-4}. Also it should be clear that finding the optimum PA in the low SNR range will not improve the performance much, and therefore no need to allocate powerful computational resources for it. For the high SNR range, few operations are enough to provide the optimum performance.

To speed up the convergence of $\mathbf{K}_{opt}$, the BS can have a database that contains the best initial guess of each SNR value. This way the number of operations required will be minimized and the system resources are used efficiently.

The feedback load does not increase much when using OPA-LSSTC since we have assumed that the channel changes slowly, and the CSI need to be sent only if the channel state changes.

VII. Numerical Results

In this section we illustrate the numerical results of the proposed PA scheme for LSSTC systems with different modulation schemes and transmitter configurations. In all the simulations conducted in this work, the STBC encoders used Alamouti's STBC matrix with unity rate. Figure 2 shows a fair comparison between different transmitter configurations of the LSSTC system in terms of the SER, obtained from both the EPA-LSSTC analysis and simulation. The three configurations use a total number of transmit antennas, $N_T = 8$, and the receiver is equipped with 4 antennas. In this comparison a different modulation scheme is used such that the spectral efficiency would be the same for all of them, which is set to 4 bps/Hz. It is clear that the simulation makes a nearly perfect match to the analytical results, which demonstrates the validity of the analysis methods we have proposed. A 16×4 OPA-LSSTC employing QPSK modulation with $K = 4$ and $L = 2$ is considered. The optimum PA for each layer versus E_s/N_0 is plotted in Figure 3, where it can be seen that at high SNR, the impact of error propagation is more dominant than the noise. It can be seen from Figure 3 that the SER is dominated by

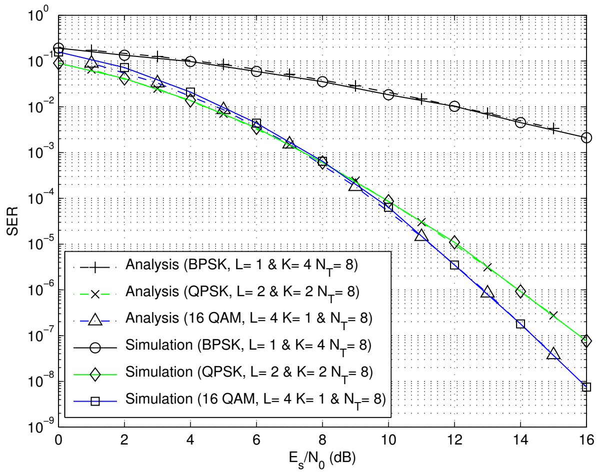

Fig. 2. SER of LSSTC employing non-ordered SGIC at 4 bps/Hz and different modulation schemes with $N_T = 8$ & $N_R = 4$ (comparing VBLAST to LSSTC fairly).

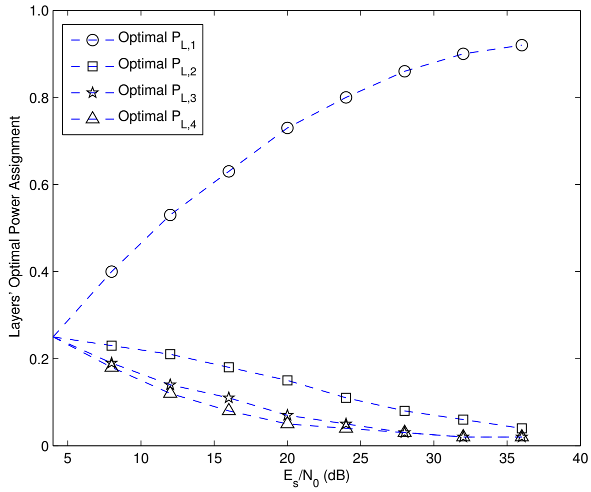

Fig. 3. Optimum power assigned for each layer for a 16×4 OPA-LSSTC scheme employing QPSK modulation with $K = 4$ & $L = 2$.

the first layer, and that the detection errors in the first layer would cause severe errors to the following layers. Therefore, the optimum PA scheme suggests assigning the earlier layers higher power than the later ones as the SNR increases. Note that the first layer gets most of the transmit power at high SNR since it is the weakest layer that has the lowest diversity order among all layers. In Figure 4, we plot the SER of a 16×4 LSSTC system employing QPSK modulation with $K = 4$ and $L = 2$. We compare two cases, PA-LSSTC with equal power allocation (EPA-LSSTC), and the PA-LSSTC with optimum power allocation (OPA-LSSTC). Our SER analysis is shown to be very accurate as compared to simulation results. It is observed that the proposed OPA-LSSTC has about 2.7 dB gain at a SER of 10^{-4} compared to EPA-LSSTC. This shows the superior performance of the proposed scheme.

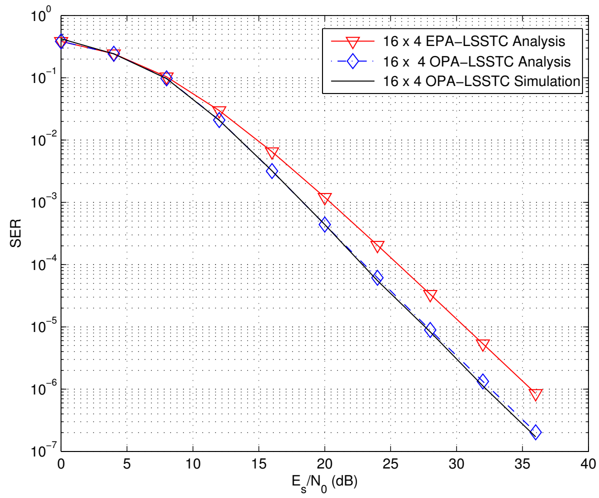

Fig. 4. SER of 16×4 LSSTC system using PA-LSSTC scheme employing QPSK modulation with $K = 4$ & $L = 2$.

VIII. Conclusions

In this paper we investigated the performance of single-user PA-LSSTC. We derived an expression for the probability of error for PA-LSSTC employing BPSK that includes the diversity gain of STBC and the SNR gain of beamforming. The expression also includes other modulation schemes, such as, M-ary PSK and M-ary QAM. The analytical results match the simulation results. Also the benefits of OPA-LSSTC in improving the performance were demonstrated. It was shown that the OPA-LSSTC for some structure can provide about a 2.7 dB gain over the EPA-LSSTC of the same structure.

IX. Acknowledgements

The authors would like to thank the support provided by KFUPM under grant no. SB070005 and by KACST under NSTIP grant no. 08-ELE39-4.

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