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A REVIEW ON BELL LABS LAYERED SPACE TIME ARCHITECTURE (V-BLAST)

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Abstract— *The paper reviews the Bell Labs Layered Space-Time Architecture (BLAST) for wireless communication. This approach involves usage of multiple antennas at both the transmit and receive ends. The paper's major aspect deals with the study of the two important derivatives -Vertical and Diagonal BLAST .First, the key distinctions in the architecture when we have and when we do not have channel side information at the transmitter are investigated, and theoretical capacity bounds are derived for them. The obtained results show linear increase in capacity with the number of antennas which leads to very high spectral efficiencies in the range of 20-40 bps/Hz at realistic SNRs and bit error rates. Furthermore the paper also includes a brief survey of common decoding techniques.*

Keywords: *V-BLAST, FADING CHANNELS.*

1. INTRODUCTION

The growth of the wireless industry both for the cellular networks and the internet is providing an opportunity for rapid strides in science. Most of the world has already shifted to the third generation of mobile technology, while the fourth generation stands at our doorstep. The Local Area Networks (LAN) are readily being shifted to Wireless LANs and are even extended to cover larger areas and provide faster speeds via the Wireless Wide/Metropolitan Area Networks. On par with this, the evolution of multimedia applications, better web interfaces (like HTML5) have all led to a demand for ever higher data rates. Since the early days, the fundamental metric used to assess any communication system has been capacity - the highest data rate at which reliable communication is possible. In [1] the authors appropriately mention that Space is the next frontier to be exploited for meeting these demands and substantiate the idea experimentally. Over the past decade this has led to a Shift from traditional one antenna systems to multiple antenna systems at both the transmit and receive ends. However the problems of scattering continued to haunt these systems, until [2] proposed a method to use the rich scattering in the environments to obtain an additional boost in performance (capacity). This approach developed at the Bell Labs, was termed BLAST. BLAST, differs from common multiple access techniques used in single-user-mode, i.e. driving all the transmitters from a single user's data which has been split into sub streams. In comparison to code-division or spread-spectrum techniques, the total bandwidth utilized in a BLAST system is almost Equivalent to the symbol rate. Also, unlike frequency-division and time-division, the entire system bandwidth is used simultaneously by all the transmitters for the entire time. The following paper is divided as follows. Few aspects of the wireless fading channel are discussed in section II followed by section III which covers the two basic MIMO architecture, and formulates their capacity measures. Further, in section IV the case of fast fading channels are considered, and and advantages V-BLAST algorithm provides are seen. Section V compares the decoding procedures and MMSE-SIC (V-E) decoding is found to help achieve capacity. In the case of slow fading channels, the use of D-BLAST is considered, and section VI gives an overview of this. Finally, the conclusion is presented in section VII. Theoretical studies in the past decade have revealed that the multiple antennas used in both the transmitter and receiver sides of a communication link, termed Multiple Input Multiple Output (MIMO) scheme, play a role in increasing the system capacity to an enonnous amount as well as handling multipath fading problem [1-3]. Techniques used to exploit the high-capacity nature of a MIMO system include Layered Space-Time architectures, namely Diagonal Bell Laboratories Layered Space-Time (DBLAST)

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[3] and Vertical Bell Laboratories Layered Space-Time (V-BLAST) [1].

In these architectures, the data stream is de multiplexed so as to yield sub streams with equal transmission rates. All sub streams are simultaneously transmitted from transmit antennas using the entire frequency bandwidth, resulting an increase of the transmission rate. D-BLAST uses a diagonally-layered coding structure to spread code blocks in space and time. This scheme enables the data rates to grow linearly in proportion to the number of antennas [1]. The implementation complexities of D-BLAST triggered the invention of V-BLAST, in which the demultiplexed data stream undergoes the process of independent bit-to-symbol mapping. In V-BLAST architecture inter-sub stream coding is not required [1]. This property encourages the simplicity offered by this scheme as well as its capability to realize high spectral efficiency.

2. WIRELESS COMMUNICATION FADING CHANNELS

Before heading to the topic of BLAST, the fading channels and their estimation techniques in the context of Orthogonal Frequency Division Multiplexing (OFDM) are described.

A. Fading Channels

The real-world communication channels, experience attenuation due to a variety of reasons leading to changing channel properties, termed fading [3]. The multiple paths a signal can take from the transmitter to the receiver and their interference are of special concern. Based on the amount of time taken for a channel to significantly change, fading channels are classified into slow fading channels and fast fading channels. A fast fading channel varies significantly over one time-scale of communication, and has a coherence time much less than the symbol duration, an effect of multi-path signal interference. On the other hand, a slow fading channel shows little variation over a few symbol durations, and is usually caused by shadowing effects. The major impact of channel fading is clearly seen on the error probability pe. For the typical Additive White Gaussian Noise (AWGN) channel pe decreases exponentially with increasing Signal to Noise Ratio (SNR), while for fading channels, pe is just inversely proportional to the SNR. The fading channel is typically modeled by the Rayleigh distribution, commonly used to describe statistical time varying nature of the received signal in cases involving no direct line-of-sight propagation path.

For the rest of the paper, the channels are assumed to be frequency flat channels, i.e. channels whose frequency response does not vary significantly within the given signal bandwidth (BW) or coherence BW is larger than signal BW. However, slow fading and fast fading channels are considered separately.

B. Channel Estimation

The information of the channel is quite a crucial aspect of Wireless communication. The channel estimation techniques in the OFDM context are explored, as they can be easily extended to any case. There are two main ways of obtaining this information - blind channel estimation and a pilot-based technique.

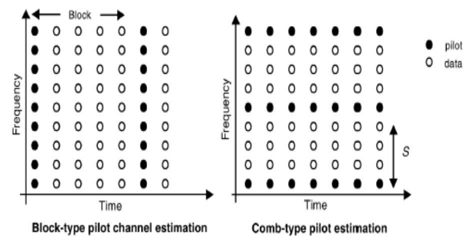

Figure 1: Block and Comb type pilot estimation techniques [5]

C. SYSTEM MODEL

The main advantage of blind channel estimation is that no overhead is required on the actual data for the channel estimation. The estimation algorithms usually use second-order statistics, and achieve smaller estimation variance compared to the other methods. However, they assume that the zeros of the channel are inside the unit circle, or channel phase information is not obtained. To counter this problem, second order cyclo stationary statistics are used. Antenna pre coding is used in [4] and better results are claimed. Blind channel estimation is typically used in slow fading channels. Pilot based techniques [5] are classified into 2 categories depending on how the pilot signal is transmitted. They are illustrated in Fig. 1.

In the block-type pilot, all frequency sub-carriers are transmitted as pilot after certain periods of time. Consequently if the channel does not change during the block duration, this technique is used for channel estimation. The block period is chosen depending on the duration for which a channel can be assumed constant and the amount of permissible overhead on the data. The typical estimators are based on Least Squares (LS) and Minimum Mean Square Error (MMSE).

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The second is comb-type pilot in which a certain subcarrier always carries the pilot information. These sub-carriers are spaced S sub-carriers apart, assuming that the channel estimate for that sub-carrier is used for its neighbors too. The estimators used for this type of pilot are LS with 1D interpolation, maximum likelihood estimator and a Parametric Channel Modeling-based estimator.

MIMO System

Multiple Input Multiple Output (MIMO) systems have recently emerged as a key technology in wireless communication systems for increasing both data rates and system performance. Techniques that use arrays of multiple transmit and receive antennas may offer high capacity to present and future wireless communications systems, which place severe demands on current spectral resources. Multiple-input multiple-output (MIMO) systems provide for a linear increase of capacity with the number of antenna elements. Multiple antennas used in both the transmitter and receiver sides of a communication link, termed Multiple Input Multiple Output (MIMO) scheme, play a role in increasing the system capacity to an enormous amount as well as handling multipath fading problem. Techniques used to exploit the high-capacity nature of a MIMO system include Layered Space-Time architectures, namely Diagonal Bell Laboratories Layered Space-Time (DBLAST) and Vertical Bell Laboratories Layered Space-Time (V-BLAST).

3. MIMO TRANSCEIVER ARCHITECTURES

The knowledge about the channel is the governing factor in the design of transceiver architecture. Especially the channel side information (CSI) at transmitter side is crucial, and leads to two main approaches

A. Full CSI

First, consider the case when the channel is known both at the transmitter and the receiver [6] (Ch.7). For simplicity of notation, a time-invariant channel is analyzed. Let nt and nr be the number of transmit and receive antennas. Then,

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \qquad (1)$$

Where $y \in C^{nr}$, and $x \in C^{nt}$ are the received and transmitted signals; w~ CN(0,N0Inr) the white Gaussian noise and H the nr~nt channel matrix.

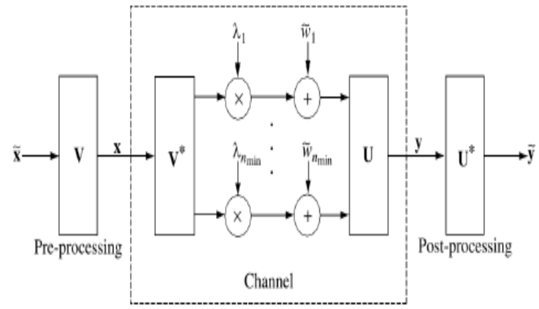

Figure 2: Conversion of MIMO channel into parallel channel via SVD [6]

From the basics of matrix algebra, **H** is decomposed using the singular value decomposition to

$$\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^* \qquad (2)$$

Where **U** and **V** are unitary rotation matrices and Λ is a diagonal matrix with diagonal elements as the ordered singular values λ_i of **H. H** can be expressed as a linear combination of the product of column vectors of the unitary matrices.

$$\mathbf{H} = \sum_{i=1}^{n_{\min}} \lambda_i \mathbf{u}_i \mathbf{v}_i^* \qquad (3)$$

Further, rotated signals are defined as Then (2) allows to rewrite (1) as

$$\tilde{y} = \Lambda\tilde{x} + \tilde{w} \qquad (4)$$

$$\tilde{y}_i = \lambda_i \tilde{x}_i + \tilde{w}_i; \text{ for } i = 1, 2, \ldots, n_{\min} \qquad (5)$$

$$C = \sum_{i=1}^{n_{\min}} \log\left(1 + \frac{P_i^* \lambda_i^2}{N_0}\right) \text{bits/s/Hz} \qquad (6)$$

The result is that the channel is split into parallel Gaussian Channels and the resultant architecture is shown in Fig. 2.

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The capacity of such a channel is now given by,where, P*t are the powers allocated to each sub-channel via the water filling solution [7], with a total power (P) constraint such that ΣI p*I = p .This can be extended to fading channels easily, since channel knowledge is assumed at both ends

B. CSI at Receiver

Now, the case when we do not have any information regarding the channel at the transmitter is considered. For simplicity, a time-invariant, but unknown channel is evaluated. In this case, the independent data streams, nt of them, area arbitrarily multiplexed via a unitary matrix Q, which is not necessarily dependent on the channel matrix H. This is the VBLAST transceiver architecture introduced in [8] and is seen in Fig. 3. Note that the power of kth stream, Pk is such that,∑kPk ≤P holds true, and the total rate R =∑k Rk .The covariance matrix of the transmitted signal x, along with the multiplexing matrix Q, is defined as

$$K_x := Q\,\mathrm{diag}\{P_1, \ldots, P_{nt}\}Q^* \quad (7)$$

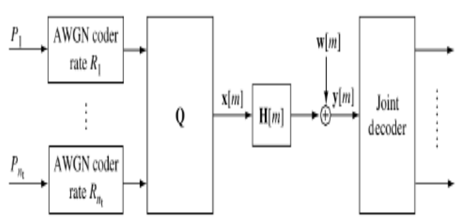

Figure 3: V-BLAST Architecture over MIMO channel [6]

The geometric sphere-packing approach [9] is used towards deriving capacity bounds. The idea is to see how many received code words (or spheres with noise) fit in a large sphere of possible received vectors. These are constrained such that no overlap of codeword spheres is allowed and the definition of capacity as a measure of error-free communication is valid Using this to compute the maximum possible rate, for a communication over a block of time symbols of length N, the received vector, of length nr N, lies with high probability in an ellipsoid of volume proportional to det(N0Inr +HKxH*)N, and hence the maximum number of code words that can be packed are

$$\frac{\det(N_0 \mathbf{I}_{n_r} + \mathbf{H}\mathbf{K}_x\mathbf{H}^*)^N}{N_0^{n_r N}} \quad (8)$$

Thus, a capacity formulation for the time-invariant case of the V-BLAST architecture is given by

4. V-BLAST AND FAST FADING CHANNELS

In this section, the fast fading channels are specifically considered and the case with CSI at receiver only is analyzed. For fast fading channels, the capacity is still the dominant criteria (unlike outage for slow fading channels). By coding over multiple coherence time intervals, a long-term average rate is derived from (9) as

$$C = \mathbb{E}_{\mathbf{H}}\left[\log\det\left(\mathbf{I}_{n_r} + \frac{1}{N_0}\mathbf{H}\mathbf{K}_x\mathbf{H}^*\right)\right] \quad (9)$$

The task is to now choose a suitable covariance matrix Kx as a function of the channel statistics. Note that the actual realization of the channel is still an unknown. Now, consider the case where there are few time-invariant dominant paths, then the optimal multiplexing system is in the directions of the eigen vectors of H*H. On the other extreme, if there are many paths (non-zero) in each of the angular bins, then equal power allocation would be favorable[6] (Ch.8). For the specific case of equal power allocation, and independent multiplexing, Q = Int , (7) is simplified to

$$\mathbf{K}_x = \left(\frac{P}{n_t}\right)\mathbf{I}_{n_t} \quad (10)$$

Further, substituting the above in (10), and using the fact that ʎi are singular values of the channel matrix H, and defining SNR = P/N0, the capacity is computed as

$$C = \mathbb{E}\left[\sum_{i=1}^{n_{\min}} \log\left(1 + \frac{\mathrm{SNR}}{n_t}\lambda_i^2\right)\right] \quad (11)$$

The obtainable capacities are now compared for the case of fast fading channels, with and without channel knowledge at the transmitter using (6) and

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(11). It is apparent that when the transmitter knows the channel, power to each antenna is allocated depending on the sub-channel gains. However,

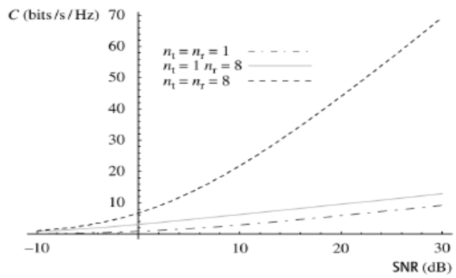

Figure 4: Comparing capacity for SIMO and MIMO channel at High SNR [6]

When the transmitter does not know the channel, but there is rich scattering in the environment ensuring sufficient randomness, the optimal power allocation strategy is to allocate equal power to all antennas. To gain an insight into the variation incapacity with SNR and number of antennas, (11) is simplified for certain scenarios. 1) High SNR Case: Jensen's inequality when applied to (11) Gives us the simplification

$$\sum_{i=1}^{n_{\min}} \log\left(1+\frac{\mathrm{SNR}}{n_t}\lambda_i^2\right) \le n_{\min}\log\left(1+\frac{\mathrm{SNR}}{n_t}\left[\frac{1}{n_{\min}}\sum_{i=1}^{n_{\min}}\lambda_i^2\right]\right) \tag{12}$$

At high values of SNR, it is seen from (11) and (12), that

$$C \approx n_{\min}\log\frac{\mathrm{SNR}}{n_t} + \sum_{i=1}^{n_{\min}} \mathbb{E}[\log\lambda_i^2] \tag{13}$$

The significant point to draw from the above equation, is that the capacity increases linearly with the increase in both number of receive and transmit antenna. However, it is important to note that this increase is dependent on the significant point to draw from the above equation, is that the capacity increases linearly with the increase in both number of receive and transmit antenna. However, it is important to note that this increase is dependent on the minimum number of antennas at each end; hence, a SIMO or MISO system will not achieve the same capacity gain. This how's that the degree-of-freedom gain is far more significant at higher SNR values. Fig. 4 clarifies the above point. The difference between capacities of SIMO and SISO channels is not much in the high SNR regime, however, the impact of MIMO is quite strong.

2) Low SNR Case: On the other hand, in the low SNR regime, (11) is simplified using log2(1 + x) x log2 e when
x << 1, which gives

$$C \approx n_r \mathrm{SNR}\log_2 e \text{ bits/s/Hz} \tag{14}$$

In contrast to the high SNR case, it is clear here that the power gain is significant at lower SNR values, and hence the linear dependence on the number of receives antennas. Also note that the effect of channel randomness no longer significantly contributes to any increase in capacity. Fig. 5 illustrates the point by showing that at low SNRs of around -20 dB, the capacity for the SIMO and MIMO channels are very similar.

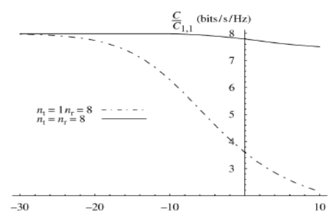

Figure 5: Comparing capacity for SIMO and MIMO channel at Low SNR [6]

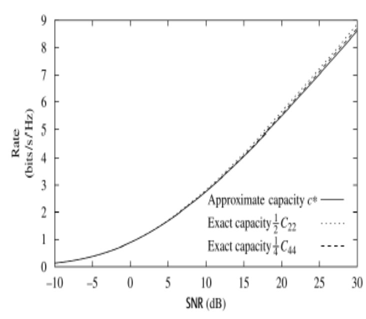

Figure 6: Comparison between the capacity values (scaled) for small n [6]

3) Number of Antennas: Let us now shift our attention to studying the effect of increase in number of antennas on the capacity at any range of SNR. It was seen earlier that at low SNR, it is important to have high number of receive antennas; while at high SNR it is important to have both high receive and

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transmit antennas. For simplicity, consider nt = nr = n.
(11) is now rewritten as

$$C_{nn}(\mathrm{SNR}) = \mathbb{E}\left[\sum_{i=1}^{n} \log\left(1 + \mathrm{SNR}\left(\frac{\lambda_i}{\sqrt{n}}\right)^2\right)\right] \qquad (15)$$

5. DECODING TECHNIQUES FOR V-BLAST

Let us consider that Q = In, i.e. independent data streams are multiplexed over the channel for simplicity. The complexity of the ML decoding technique has led to the development of multiple suboptimal techniques [11], [6](Ch.8) .

A. Joint ML Decoding

The capacity achieving joint ML decoder, is a viable option when the number of antennas is limited. However, since it involves decoding of the complete data vector, the complexity of this method grows exponentially with the number of antennas. This is seen from the equation that solves the joint ML detection problem, where the transmitted signal x belonging to some constellation C is decoded, from the received signal through a channel H as

$$\hat{\mathrm{x}} = \arg\min_{x \in C} \|\mathrm{y} - \mathrm{Hx}\|^2 \qquad (16)$$

B. Linear Decorrelator

In this method the focus is on one data stream of the received vector, say kth, as y[m] = hkxk[m]+∑i≠k hixi[m]+w[m], where hi are columns of the channel matrix H. To separate the kth stream from the others, the received signal is projected using some Qk, onto a subspace orthogonal to the subspace spanned by h1,…., hk-1, hk+1,….,hnt . The nulling operation is successful as long as hk is not a linear combination of the others. Further, a matched filter (MF) is applied sometimes, to maximize the output SNR of the estimated signal. This combination of projection followed by MF is also called zero-forcing (ZF) receiver

$$\tilde{\mathrm{y}}_k := \mathrm{Q}_k\mathrm{y} = \mathrm{Q}_k\mathrm{h}_k x_k + \tilde{\mathrm{w}}; \quad \hat{x}_k = (\mathrm{Q}_k\mathrm{h}_k)^*\tilde{\mathrm{y}} \qquad (17)$$

C. Successive Cancellation

The above linear decorrelator can be used at each step with successive interference cancellation (SIC) of the estimated data stream. This enables us to project onto significantly reduced subspace. For example, for decoding of the kth stream, projection is computed on a subspace orthogonal to the one spanned by hk+1,…., hnt . So, each decoder sees only “down-stream interference”. However, error propagation is a serious problem to this approach. Another crucial aspect of this scheme is the order in which signals are to be cancelled. Typically, the signals are arranged in order such that the stronger signals are cancelled earlier, while the weaker ones later. [8] Shows that maximizing the minimum post-detection SNR for each detection, can give an optimal detection ordering. A short mathematical formulation would be to subtract the decoded estimates of signals xi from the original received signal y, and use this yk for further processing.

$$\tilde{\mathbf{y}}_k = \mathbf{y} - \sum_{i=0}^{k-1} \mathbf{h}_i \hat{x}_i \qquad (18)$$

E. MMSE-SIC

A natural extension to the MMSE decoder is to integrate it along with SIC. It is observed that this decoder with equal power allocation at the transmitters, achieves capacity for the i.e. Rayleigh fading channel. Fig. 7 compares the performance of various decoding strategies, and provides a ratio of the rate achieved to the capacity for a 8×8 MIMO system over wide range of SNR.

F. Complexity Comparison of Decoding Techniques

Maximum Likelihood The only optimal detector, however has exponentially increasing complexity with number of antennas and alphabet. Hence, it is rarely used in practice for large systems.
Matched Filter This is a suboptimal detector. Assumes the interference as noise. However it is seen to work well for the low SNR regimes. It is also the lowest complexity detector, as it basically computes a correlation. Usually SIC is not used along with MF.
Linear Decorrelator Another suboptimal detector, which complements the matched filter. This works well in Fig. 8. D-BLAST Space-Time Layered Encoding Flow [2] high SNR regimes. Requires computing the projection to orthogonal subspaces to null the interferers. Higher complexity than MF, but can be used along with SIC to further improve performance.

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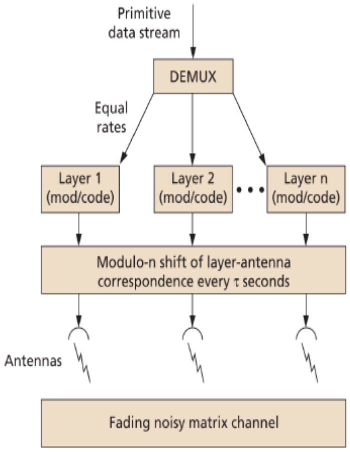

Figure 7: D-BLAST Space-Time Layered Encoding Flow [2]

MMSE The capacity achieving detector with SIC, however is the most complex in practice. It also requires the knowledge of noise statistics. Possible to prove mathematically that it reduces to MF and ZF in the low and high SNR regimes respectively.

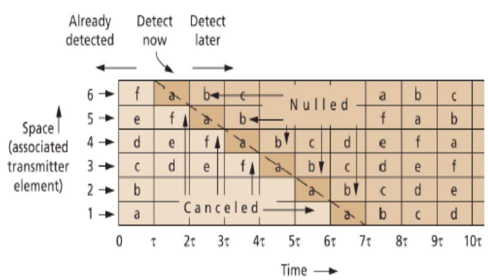

Figure 8: D-BLAST Space-Time Layered Decoding [2]

This association is cycled periodically over a duration Makes sure that each of the n encoded sub-streams share a presence over all the transmit antennas, and thus none of them is vulnerable to the case of one antenna being in deep fade. This dismisses the possibility of loss of data due to a bad sub channel that was a major concern in the V-BLAST Scenario. This procedure also ensures that all n constituents are identical in nature, and the balance allows the usage of the same constellation for each sub-channel. Each channel is essentially the same regarding the opportunity for coding

Decoding Procedure D-BLAST

We now turn to the receiver side, and look at the decoding procedure employed in D-BLAST via an example. Fig. 8 illustrates it for the case of 6×6 MIMO system. Let us consider a sequence of labels abcdef. The figure describes the step of detecting the diagonal corresponding to the label a. The complete a layer, comprises of 6 parts, which occur during the time intervals starting at r up to 7r where r represents the periodic cycling carried out at the transmitter end described earlier. It is clear that the layers located below this a layer, are assumed to be successfully decoded and hence cancelled and the layers above are yet to be detected and hence they are nulled. Thus, during r to 2 r we have direct decoding; from 2r to 3r we null the interference from transmitter 6; from 3r to 4r we null transmitter 5 and 6 and so on. For the simplistic example of block coding that we have chosen, one layer (e.g. a) could correspond to one block, however, associating more than one block (via convolution coding) sometimes leads to higher bandwidth efficiency [10].

Comparison of V-BLAST and D-BLAST

The essential difference between D-BLAST and V-BLAST lies in the vector encoding process. In D-BLAST, redundancy between the substreams is introduced through the use of specialized inter sub stream block coding. The D-BLAST code blocks are organized along diagonals in space-time. It is this coding that leads to D-BLASTs higher spectral efficiencies for a given number of transmitters and receivers. In V-BLAST, however, the vector encoding process is simply a demultiplex operation followed by independent bit-to-symbol mapping of each sub stream. From [2] it is seen that D-BLAST achieves spectral efficiencies in the range of 40 bps/Hz at 24 dB SNR for a 8 × 8 MIMO system for a 1% outage probability, while V-BLAST for an 8 × 12 system is seen to achieve around 25 bps/Hz at 21 dB SNR for a bit error rate around 1% [8]. This difference can also appear from the different symbol durations that the two systems adopt. Thus at the cost of higher architecture complexity (diagonalization), D-BLAST performs better than the V-BLAST[10].

6. CONCLUSION

In this paper the motivation for using a layered space-time approach towards wireless communication is described. The rich-scattering environment, until now thought to be a major drawback, is exploited for enhancing performance. MIMO architectures for CSI at receiver only, or both transmitter and receiver are studied, focusing more on the former, BLAST. It is seen that the V-BLAST architecture, could reach capacities close to Shannon's limit. In MIMO systems with equal number of transmit and receive antennas, the capacity is shown to scale linearly with

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the number of antennas. The typical decoding techniques are compared and MMSE is chosen as the alternative with the aim of providing highest SINR. Along with interference cancellation, it is shown to achieve best capacity results. Finally another related architecture which could be used in case of slow fading channels, D-BLAST is discussed. It involves the diagonalization of space-time via periodically cycling the bit-stream and transmitter antennas. Overall, as [2] motivate, there can be a possibility to include multiple antennas in laptops for higher operating frequencies. Then the corresponding improvement in spectral efficiency, a number much higher than even the expected standards of Long Term Evolution (LTE) technologies is highly promising.

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