# Performance Evaluation of Indoor Wireless Systems Using BLAST Testbed

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*Abstract*- **BLAST[1] has been shown to provide high capacity wireless communications by using multiple antennas at both transmitter and receiver. We have built a narrowband wireless BLAST testbed with multiple transmit and receive antennas. In this paper, we examine the performance of the VBLAST [2, 3] by choosing the antenna configurations and performing link adaptation. It is shown that adapting the number of transmit antennas achieves remarkable performance improvement. To further demonstrate the effectiveness of the testbed, we use over-the-air error traces to simulate a H.263+ video transmission.**

## I. INTRODUCTION

The Bell Labs Layered Space-Time (BLAST) [1] architecture utilizes multi-element antenna arrays at both transmitter and receiver to provide high capacity wireless communications in a rich scattering environment. It has been shown that the theoretical capacity increases approximately linearly as the number of antennas is increased. Two types of BLAST realizations have been developed, vertical BLAST (VBLAST) [2, 3] and diagonal BLAST (DBLAST). The VBLAST is a simplified version where channel coding is applied to individual sub-layer, each corresponding to the data stream transmitted by a single antenna. The DBLAST applies coding not only across the time, but also across the antennas (sub-layers), and implies higher complexity.

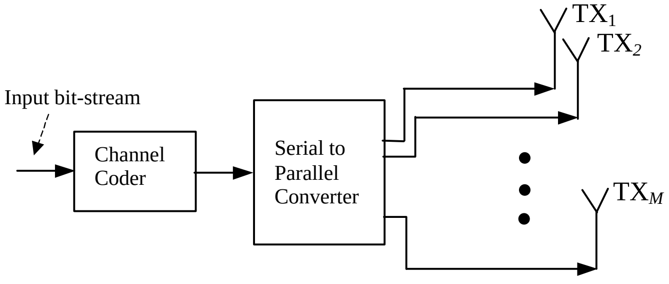

Figure 1. Transmitter architecture

We have built a narrowband wireless testbed based on the VBLAST, which is used for verifications and performance evaluations of different algorithms related to the BLAST wireless communication architecture. To illustrate the high capacity gain provided by BLAST, we perform transmission of H.263 video coded at 230kbps over the VBLAST testbed and the performances under different channel designs are studied. The transmitter architecture is given in Figure 1.

## II. NARROWBAND VBLAST TESTBED

Let us now describe hardware components of the narrowband VBLAST wireless testbed. Radio frequency (RF) front-end of the testbed consists of an antenna array, and the corresponding array of analog RF transmitters and receivers. In this particular experiment we used up to eight transmit and eight receive antennas. The carrier is at 1.95 GHz and the signal bandwidth is limited to 30KHz. Both transmit and receive antenna elements are kept half wavelength apart. Neighboring antennas are alternately vertically and horizontally polarized.

The baseband digital signal processing is executed using a DSP multiprocessor system: Pentek 4285 [4]. It consists of eight Texas Instrument's TMS320C40 DSPs, offering total processing power of 400 MIPS. Interfacing towards the baseband inputs and outputs of the array of analog RF transmitters and receivers is realized using a system of multi-channel A/D (Pentek 4275 [5]) and D/A (Pentek 4253 [6]) converters, respectively. The maximum sampling rate, per a baseband channel, is 100 KHz.

- Modulation and Data Formats

In this particular experiment we use QPSK modulation format, transmitting at 25ksym/sec, per sub-layer (i.e., per antenna). Further, the symbols are organized as follows (see Figure 2.):

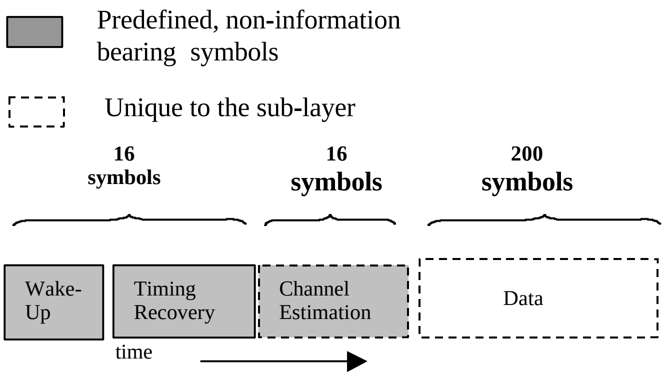

Figure 2. Frame Structure

Symbols 1 to 16 are used for synchronization, i.e., frame and symbol timing recovery. Note this part of the frame is identical for all the sub-layers. Symbols 17 to 32 compose a training sequence, which is used for estimation of the channel response. Between the sub-layers, the sequences are mutually orthogonal and with equal transmission power. Walsh sequences of length 16 are applied. Symbols 33 to 232 are information bearing symbols. Considering the QPSK format, 400 bits are transmitted per frame, per sub-layer.

- Baseband DSP Blocks

Let us now briefly describe the baseband digital signal processing blocks that are applied at the receiver.

*Detection of the frame start* - In this block, we wait on a sufficiently strong signal that indicates the initialization of data transmission. At the transmitter, as said earlier, the synchronization sequence precedes the information-bearing signal. The sequence is supposed to indicate the start of the transmission for the receiver.

*Symbol timing recovery* - After the strong signal is detected, the received signal, which is four times oversampled (i.e., four samples per symbol period), is crosscorrelated with predefined synchronization sequence, that exhibits good autocorrelation properties (in this case we apply a binary Barker sequence [4]). A crosscorrelation lag that results in highest crosscorrelation is used to establish symbol synchronization.

*Mitigation of hardware induced intersymbol interference (ISI)* - At the transmitter side, the spectrum of the signal is shaped with an analog lowpass filter. Further, the processing at the RF front-end of the transmitter additionally distorts the spectrum. Consequently at the receiver, in order to mitigate the ISI caused by the spectrum shaping and its linear distortions, a fixed coefficient FIR filter is applied on received signal. The coefficients of the filter are precalculated using laboratory measurements of the received spectrum and its inverse.

*Estimation of the channel response* - The estimation is based on using mutually orthogonal training sequences between the sub-layers. As said earlier apply Walsh sequences. Because the sequences are mutually orthogonal, the correlator based estimation scheme will provide the maximum-likelihood estimate [7] of the channel matrix.

*The VBLAST Algorithm* - Based on the channel responses estimated in the previous block, we perform VBLAST algorithm [2, 3]. Note that the decision on transmitted data can be performed in this step, but instead, the soft and normalized outputs are passed to the channel decoder.

- Channel Coding

In this experiment, each frame consists of 232 QPSK symbols, where 32 symbols are dedicated to synchronization and training. Therefore, 200 QPSK data symbols are transmitted through each antenna. To achieve better coding efficiency, one single convolutional code is applied to all the sub-layers. We employ rate 1/2 and 1/3 convolutional codes of constraint length 8. In addition, a rate 2/3 code is obtained by puncturing the output of the rate 1/3 code. Using 8x8 system as an example, by multiplexing the coded bits into 8 sub-layers, an interleaving of depth 8 is achieved naturally. At the receiver, the VBLAST algorithm is applied to extract the soft input, which is forwarded to the channel decoder. The data rate per transmit antenna when there is no coding can be computed as 200*2/(9.28e-3)= 43.10kbps. The frame structures for different coding rates are illustrated in Table 1 assuming 6 transmit and 8 transmit antenna elements.

In the previous publication [8], we have shown that with a rate 2/3 convolutional code, the frame error rate (FER) can be reduced from 30% to 3% which can be further reduced by error handling techniques at higher layers such as Automatic retransmission ReQuest (ARQ). It was also shown that the optimal coding rate depends on the SNR, and the system should employ link adaptation to maximize the link throughput.

Table 1. Frame Structure

9.28ms frame, 200 QPSK symbols per frame per Tx antenna

| Coding Rate | 6Tx | | 8Tx | |
|---|---|---|---|---|
| | Info | throughput | Info | throughput |
| 1 | 2400 | 258.6kbps | 3200 | 345kbps |
| 2/3 | 1600 | 172.4kbps | 2125 | 230kbps |
| ½ | 1200 | 129.3kbps | 1600 | 172.4kbps |
| 1/3 | 800 | 86.1kbps | 1058 | 115kbps |

## III. VBLAST TESTBED PERFORMANCE

We use ($M$, $N$) to represent a BLAST system with $M$ transmit antennas and $N$ receive antennas. The concept of BLAST is to utilize both receive and transmit diversity to boost data rate, but the choice of the number of transmit and receive antenna elements depends on both performance and complexity. For VBLAST, where each transmit antenna yields spatial interference to the others, using all the transmit antennas might not yield the best performance. Therefore, for a given number of receive antennas, we need to select an optimal number of transmit antennas. On the other hand, it is well known that increasing the number of receive antennas always improves the system performance. So that the best number of receive antennas only depends on the hardware complexity.

In the following, the presented results correspond to experimentally measured data. The experiments are conduced indoors where transmitter and receiver are 20 meters apart and without the line of sight(LOS).

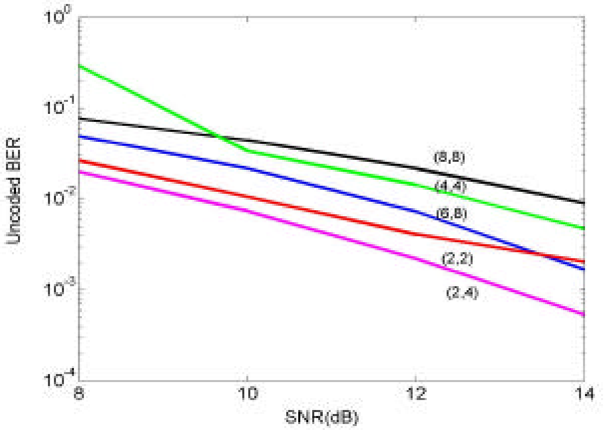

Figure 3. Uncoded BER for different antenna configurations.

First, we examine the BER performance of (2,2), (2,4), (4,4), (6,8) and (8,8) antenna configurations without any channel coding. Figure 3 depicts that (2,4) has better BER performance compared to (4,4) and (6,8) is better than (8,8). This is mainly due to that the total power constraint is kept the same independent of the number of transmit antennas during the comparison. In another words, the amount of power transmitted from each antenna would be larger for 2 transmit antenna system compared to that of 4 transmit antenna system. On the other hand, it should be noted that increasing the number of transmit antennas also improves the raw data throughput, and such tradeoff will be considered in the throughput analysis.

Next, we analyze the VBLAST performance in the presence of convolutional channel coding. The performance is evaluated in terms of the coded throughput, i.e. Rate * (1-FER) which is shown in Figure 4. The curves reflect the link adaptation by selecting the optimal coding rate between 1/2 and 2/3 that maximizes the throughput. We see that in general for large SNRs a (*M1*,*N1*) system outperforms a (*M2*,*N2*) system when $M1 \geq M2$ and $N1 \geq N2$.

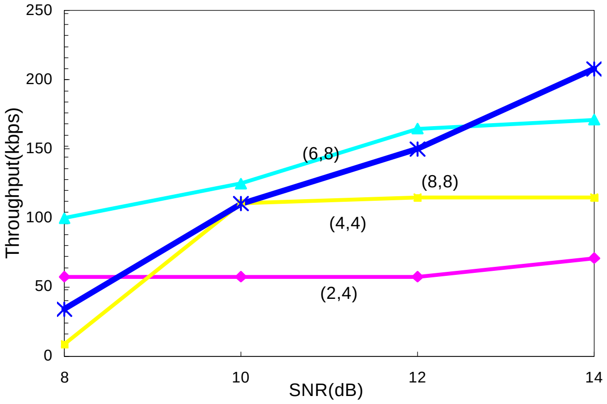

Figure 4. Throughput Performances for Different Antenna Configurations.

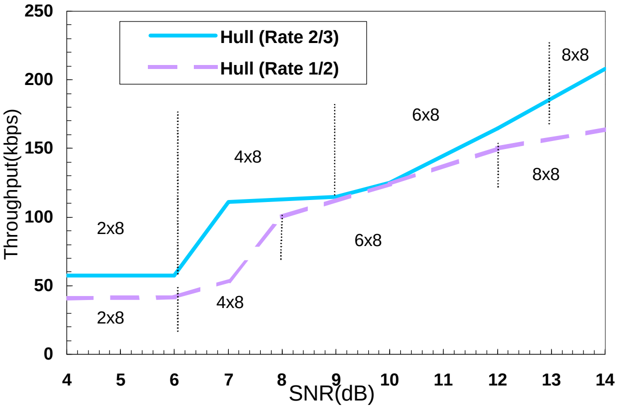

Figure 5. Throughput performances for different transmit antenna sets.

To analyze the impact of the transmit antenna elements for a given number of receive antenna elements, we fix the number of receive antenna elements to 8, and compare the throughput performances of (2,8), (4,8), (6,8) and (8,8) systems. From the results illustrated in Figure 5, we see that as SNR gradually increases, adding transmit antenna improves the system throughput. Therefore, if the hardware implementation permits, the link adaptation should include both channel coding selection and antenna configuration selection. Figure 5 also depicts that when selecting antenna configurations in a frame by frame basis is possible, varying coding rate becomes less effective. However, it should be pointed out that in this particular experiment, the coding rate choices are very limited and only QPSK modulation is used. Introducing Adaptive Modulation and Coding (AMC) while increasing modulation and coding rate choices might change the conclusion and is under further investigation.

## IV. H.263 VIDEO THROUGH TESTBED

We are interested to validate the VBLAST testbed performance by transmitting video data. The video quality is presented in terms of the Peak Signal-to-Noise Ratio (PSNR) of the video. The system structure is shown in Figure 6. We choose an H.263+ coded video sequence, with a bit rate of 230kbps at 15fps. The following error-resilience features were implemented: 1) inserting one intra frame every five frames, 2) insert sync word in each GOB (slice)[9].

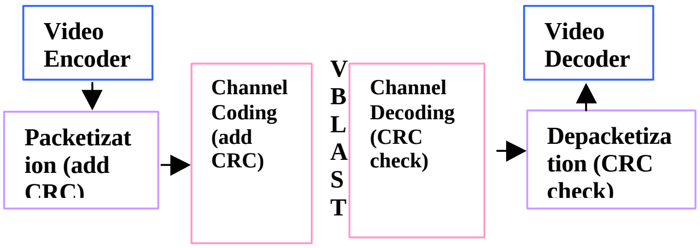

Figure 6. System Architecture

The video stream is packetized through the detection of GOB synchronization word. In another words, each GOB corresponds to one application packet, and the resulted packets are of different lengths. Each packet is accompanied by a 16-bit CRC check for content validation. Channel errors usually partially corrupt a packet. If the protocol discards a packet containing only a small part of corrupted data, it also throws out error-free data within the packet. Indeed, the media decoder can detect and tolerate a certain amount of channel errors. To support this feature, it would be possible to still forward the corrupted packet to the video decoder and let the video decoder to detect the errors. Therefore, when the packet CRC fails, we consider the following two options:

I. Discard the packet
II. Forward the packet to video decoder

On the other hand, each physical layer frame is accompanied by a 16-bit CRC check. At the receiver, nearly all the errors can be detected. This indeed provides an accurate error indication. However, in the conventional system design, the physical layer does not communicate with the application layer. And it might simply discard the frame. For video/audio, this could generate additional errors. Therefore, we have proposed to forward the frame error indication to the application layer [7]. One example would be replacing the corrupted physical layer frames as all 1s, which can be recognized by the media decoder as an invalid codeword and thus invokes error concealment to reduce or even eliminate the error effect. When video decoder is effective in terms of error detection, physical and network layer can simply forward the corrupted frames/packets to the video decoder for flexible error control. In this experiment, when CRC detects channel error, we compare three options in terms of error handling in physical layer:

A. Discard the frame
B. Forward the frame to video depacketization.
C. Replace the frame as all ones

It should be noted that by employing option I in packet level error handling, i.e. discarding the packet, the performance remains the same for option A to C. Therefore, we simply compare the following four options in terms of packet level and physical layer level error handling techniques: I, II+A, II+B, II+C.

From Figure 4 and 5, we observe that a data rate of 230kbps can be achieved when SNR is higher than 14dB. It should be pointed out that for lower SNRs we could reduce the video-coding rate to avoid packet loss and error. However, since this paper is focused on demonstrating the error handling techniques when the channel variation is difficult to predict, we choose 12 to 15dB SNR range. We use the error traces generated from the real-time testbed to simulate the video performance. The error traces reflect 1.5% to 16% FER. The PSNR performances are obtained by averaging the results from 20 experiments.

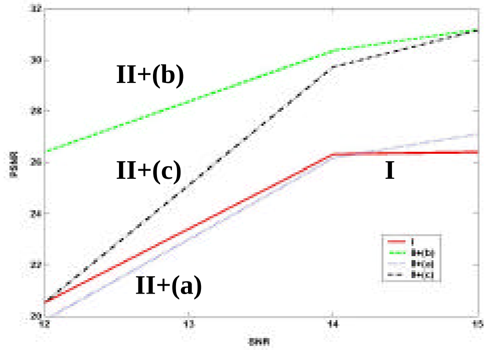

Figure 7. Video Performance

Figure 7 depicts that forwarding all the physical layer data to the application layer is the best solution for this specific experiment. The main reason is that given the environment that the testbed experiences, the number of error bits within corrupted frames is fairly small. Therefore the video decoder can easily detect and conceal the channel errors. For II+C option where the corrupted frames are filled with “1”s, we see large performance degradation at low SNRs where large number of frame errors occurs. The performance improves quickly with SNR, and there are as high as 4dB PSNR improvement compared to the other two options. From this experiment, we conclude that the protocol architecture design greatly impacts the system performance, as shown in the previous publication[7]. To support error-resilient application like video, forwarding all the information to the application layer benefits the performance.

## V. CONCLUSION

In this paper, we validate the performance of a narrowband VBLAST testbed with multiple transmit and receive antenna elements. We define the VBLAST testbed architecture by choosing the coding rate, link adaptation and the number of transmit and receiver antenna elements. It is observed that in addition to link adaptation through AMC, choosing the antenna configurations, especially the number of transmit antennas can greatly improve the system performance.

To further examine the effectiveness of the testbed, we extract the over-the-air error traces and apply them to video streams. We also compared the error handling techniques in terms of the received video quality. It is concluded that for the environments that the testbed experienced, the number of bit error is small within each corrupted frame. Under this condition, forwarding all the frames and packets to the video decoder achieves the best video performance.

We also like to point out that in wireless communications, the physical layer is usually the performance bottleneck that is difficult to improve due to large and unpredictable channel variation and multipath fading. For specific applications like multimedia data with error resilience, one can design the layer 2 and 3 (MAC, network) wisely to achieve better error recovery at the application layer. As shown in the video performance, this consideration can dramatically improve the overall performance without putting huge complexity in improving physical layer performance.

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