Performance Evaluation of the VBLAST Algorithm in W-CDMA Systems

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Abstract

In this paper we evaluate performance of the vertical BLAST (VBLAST) receiver algorithm in multiple-transmitter/multiple-receiver (MTMR) cellular W-CDMA systems. We assume that the VBLAST algorithm is executed on a symbol level (i.e, on the despreaded received signal), following a conventional bank of matched filters (correlators). Also, we introduce concept of virtual antennas. BER performance of the algorithm in presence of intra- and inter-cell multiple-access interference (MAI) is evaluated. System (Shannon) capacity is also studied. The observed system is defined based on the UMTS physical layer and corresponding channel models.

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 approximately increases linearly as the number of antennas is increased [1]. Two types of the BLAST realizations have been widely publicized: vertical BLAST (VBLAST) [2] and diagonal BLAST (DBLAST). The VBLAST is a practical algorithm that is shown to achieve large fraction of the MIMO channel capacity [2] in the case of narrowband point-to-point communication scenarios. The VBLAST is a simplified version where channel coding may be applied to individual sub-layers, each corresponding to the data stream transmitted by a single antenna. In this paper we do not apply channel coding. The DBLAST applies coding not only across time, but also across the antennas (sub-layers), and implies higher complexity. The above algorithms require explicit knowledge of the multiple-input/multiple-output (MIMO) channel response. In this paper we analyze the VBLAST performance in the case of the downlink of W-CDMA (e.g., 3G CDMA based) systems that are dominated by MAI [3,4]. Note that by wideband channel we actually assume time-dispersive (i.e., frequency selective fading) channel. As a result of the time-dispersive nature of the channel, initial orthogonality between channelization codes (e.g., Walsh codes) is corrupted at the receiver. Consequently, the intra-cell MAI is introduced (for the downlink, it is the interference between the signals from the same base-station coming from different channel delays). Note that this problem is not unique to the MIMO systems. It is also present in conventional W-CDMA single-input/single-output (SISO) systems [5].

In the following section we introduce system model. We present the transmitter and receiver architecture, and corresponding model of the received signal. Characteristics of the intra- and inter-cell interference are discussed. Concept of virtual antennas is introduced. Further, the VBLAST algorithm is described in Section III. Numerical results are presented in Section IV. We present results (in terms of mean and cumulative system capacity and bit-error-rate statistics) for different channels, number of transmit and receive antennas and cell loading (i.e., number of the channelization codes used in the cell). We conclude in Section V.

II SYSTEM MODEL

We assume a multiple-transmit antenna architecture where the number of transmit antennas is M. Considering downlink and a single user, each transmit antenna transmits an independent information stream to the user. For each user, all transmit antennas use the same channelization code (e.g., Walsh code); but between different users, channelization codes are mutually orthogonal. The system does not apply channel coding. Furthermore, transmit power is equally divided across all transmit antennas. The above assumptions assure that the multiple-transmit antenna system is equivalent to a single-transmit antenna system, with respect to the total transmitted power and use of the channelization codes, per user. Considering the downlink, all the transmitters that belong to

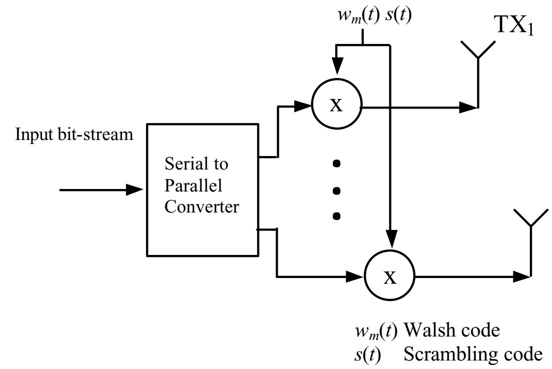

Figure 1: Transmitter architecture.

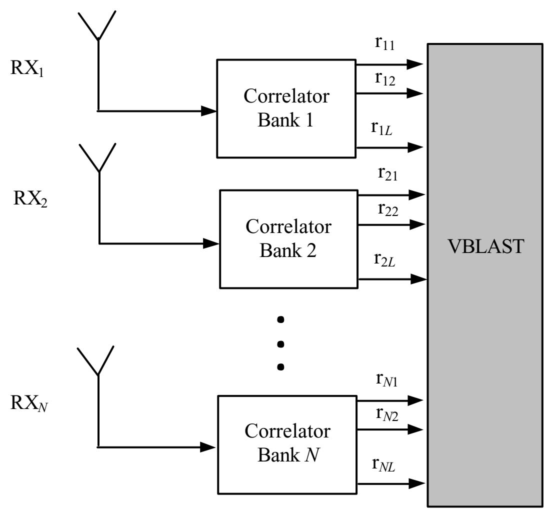

Figure 2: Receiver architecture.

the same base-station (BS) use the same long scrambling code with different long scrambling codes associated with the neighboring BSs [5,6]. The transmitter architecture is depicted in Figure 1 (where $w_m(t)$ is Walsh code for user m, and $s(t)$ is the scrambling code for the given cell).

The number of receive antennas is N. We assume that each receiver antenna (RF front-end), after the downconversion, is followed by the conventional bank of matched filters (i.e., correlators). The correlators are also denoted as fingers. The correlator bank performs despreading and finger tracking. It is equivalent to the conventional RAKE receiver, but without maximum ratio combining of the correlator outputs. Complex outputs of the correlators (one despreaded complex signal per each correlator) are fed into the VBLAST algorithm operating at the symbol rate. The VBLAST algorithm is described in Section III. The VBLAST processing is performed on the following received vector,

$$\mathbf{r} = [r_{11} \cdots r_{1L} \ \cdots \ r_{N1} \cdots r_{NL}]^\top \tag{1}$$

This vector is received once per symbol period. L corresponds to the number of the fingers per each antenna. r_{ij} denotes complex (I and Q component) output of the j^{th} finger that follows the i^{th} receive antenna ($i = 1, \cdots, N,\ j = 1, \cdots, L$). Furthermore, note that per each receive antenna there are L outputs. This may be viewed as a virtual receiver diversity, and therefore, each finger j of the antenna i, is denoted as a *virtual antenna* ij. The above set of correlator banks implicitly assumes multi-path nature of the channel. Also it may be viewed as an interface between a wideband (time-dispersive) MIMO channel and MIMO receiver. The MIMO channel response is defined by a matrix $\mathbf{H}$, whose k^{th} column

$$\mathbf{h}_k = [h_{11k} \cdots h_{1Lk} \ \cdots \ h_{N1k} \cdots h_{NLk}]^\top \tag{2}$$

corresponds to the channel response of the k^{th} transmit antenna. For h_{ijk}, i denotes the received antenna and j the finger. Considering the downlink, at a mobile, each output r_{ij} contains desired user contribution, intra-cell MAI (due to the frequency selective fading), inter-cell MAI (from the neighboring BSs) and additive white Gaussian noise (AWGN). The desired user contribution consists of the signals coming from all transmit antennas. Because of the long scrambling codes, both intra-cell and inter-cell MAI may be viewed as Gaussian random processes. Further,

$$r_{ij} = \sum_{k=1}^{M} \sqrt{\frac{P}{M}}\, d_k h_{ijk} + x_{ij} + y_{ij} + z_{ij} \tag{3}$$

P is average received power and d_k is unit variance complex data, all for the desired user. y_{ij} corresponds to inter-cell MAI, and z_{ij} to AWGN. x_{ij} is intra-cell MAI coming from different channel delays that are captured by the fingers $l = 1, \cdots, L$ for $l \neq j$. Thus,

$$x_{ij} = \sum_{k=1}^{M} \sum_{l=1, l\neq j}^{L} \sqrt{\frac{K}{G}\frac{P}{M}}\, g_{lk} h_{ilk} \tag{4}$$

where K is the number of channelization codes used in the cell, G is the spreading gain, and g_{lk} is unit variance complex Gaussian random variable. We assume that fingers ij, across all correlator banks ($i = 1, \cdots, N$), are synchronized (positioned) to the same channel delay (i.e., $\tau_{1j} = \cdots = \tau_{Nj}$, where τ_{ij} is the relative time delay of the finger j in the correlator bank i). Based on this assumption, per received vector $\mathbf{r}$, g_{kl} is the same across the receive antennas. In general, the inter-cell MAI is not spatially white, but in this paper it is modeled as spatially white AWGN. Therefore, the model of the received vector is given as

$$\mathbf{r} = \sqrt{\frac{P}{M}}\,\mathbf{H}\,\mathbf{d} + \sqrt{\frac{K}{G}\frac{P}{M}}\mathbf{Y}\,\mathbf{g} + \sigma\mathbf{n} \tag{5}$$

The matrix $\mathbf{H}$ is previously defined and has M columns and LN rows. Components d_k ($k = 1, \cdots, M$) of the vector $\mathbf{d}$ are unit variance complex data. $\mathbf{Y}$ is channel response matrix regarding the intra-cell MAI. It contains $L(L-1)M$ columns and LN rows. $\mathbf{g}$ is a vector of unit variance complex Gaussian random variables. It contains $L(L-1)M$ elements. $\mathbf{n}$ is a vector of unit variance Gaussian variables, modeling the background AWGN, inter-cell MAI and intra-cell MAI whose energy is not captured by the fingers. In order to describe the matrix $\mathbf{H}$ and $\mathbf{Y}$ we use an example for a system with $M = 2$, $N = 2$, $L = 3$ (two transmit, two receive antennas and three fingers per each receive antenna). For this particular system, the matrix $\mathbf{H}$ and $\mathbf{Y}$ are presented in the following

$$\mathbf{H} = \begin{bmatrix} h_{111} & h_{112} \\ h_{121} & h_{122} \\ h_{131} & h_{132} \\ h_{211} & h_{212} \\ h_{221} & h_{222} \\ h_{231} & h_{232} \end{bmatrix} \tag{6}$$

$$\mathbf{Y} = \begin{bmatrix} 0 & 0 & h_{121} & 0 & h_{131} & 0 & 0 & 0 & h_{122} & 0 & h_{132} & 0 \\ h_{111} & 0 & 0 & 0 & 0 & h_{131} & h_{112} & 0 & 0 & 0 & 0 & h_{132} \\ 0 & h_{111} & 0 & h_{121} & 0 & 0 & 0 & h_{112} & 0 & h_{122} & 0 & 0 \\ 0 & 0 & h_{221} & 0 & h_{231} & 0 & 0 & 0 & h_{222} & 0 & h_{232} & 0 \\ h_{211} & 0 & 0 & 0 & 0 & h_{231} & h_{212} & 0 & 0 & 0 & 0 & h_{232} \\ 0 & h_{211} & 0 & h_{221} & 0 & 0 & 0 & h_{212} & 0 & h_{222} & 0 & 0 \end{bmatrix} \tag{7}$$

Note that for $L = 1$, the model in (5) corresponds to well known narrowband case (i.e., flat fading MIMO channel). For $L = 1$ the second term in (5) does not exist.

III THE VBLAST ALGORITHM

Let us now briefly present the VBLAST scheme. We assume knowledge of the desired user channel response matrix $\mathbf{H}$. For example, an estimate of the matrix $\mathbf{H}$ may be obtained from an estimation scheme that is closely coupled with the bank of correlators [7]. In addition, we assume knowledge of the covariance matrix $\mathbf{R} = E[\mathbf{r}\,\mathbf{r}^H]$. Power ordering of the sub-layers is needed, but for the sake of simplicity, we assume that $|\mathbf{h}_1^2| \geq \cdots \geq |\mathbf{h}_M^2|$. The following steps are executed.

1. Reset the counter, $p = 1$.

2. Determine the minimum mean square error (MMSE) detector as

$$\mathbf{m}_p = \mathbf{R}^{-1}\mathbf{h}_p/(\mathbf{h}_p^H\mathbf{R}^{-1}\mathbf{h}_p) \tag{8}$$

3. Project the received vector on the MMSE detector as

$$\hat{s}_p = \mathbf{m}_p^H\mathbf{r} \tag{9}$$

   Using the above result decide upon the received data. For example, in the case of QPSK modulation $\hat{d}_p = \sqrt{\frac{1}{2}}(sgn(Re(\hat{s}_p)) + j\; sgn(Im(\hat{s}_p)))$.

4. Cancel sub-layer p contribution as

$$\mathbf{r} = \mathbf{r} - \sqrt{\frac{P}{M}}\hat{d}_p\mathbf{h}_p \tag{10}$$

5. Deflate the covariance matrix as

$$\mathbf{R} = \mathbf{R} - \frac{P}{M}\,\mathbf{h}_p\mathbf{h}_p^H \tag{11}$$

6. Increment p, $p = p + 1$, and repeat steps 2 to 6 if $p \leq M$, i.e., the above steps are performed repeatedly for all sub-layers.

The above version of the VBLAST is based on the MMSE detection. The above algorithm is identical to its original narrowband version [2]. In wideband case, the VBLAST processes the outputs of L correlators per each receive antenna, i.e, the total of LxN virtual antenna outputs are processed; while in the narrowband case, just N antenna outputs are processed.

IV NUMERICAL RESULTS

We consider downlink of a W-CDMA system. In this section, the simulations are based on the system model in (5). We assume the spreading gain of $G = 32$. QPSK modulation is applied. We present results for different number of transmit and receive antennas $M = 1, 2, 4$ and $N = 1, 4$ (e.g, for $M = 4$ in a UMTS system [5], the above scenario would correspond to uncoded data rate of $960Kbps$ per channelization code.). Note that by signal-to-noise ratio we assume a ratio between the total average received power per antenna (after the despreading) and variance of the background noise (i.e., SNR=$10\log\frac{P}{\sigma^2}$).

The entries (i.e., channel coefficients) of the matrix H and Y are generated according to

$$h_{ijk} = \sqrt{p_f(j)}\,q_{ijk} \tag{12}$$

where q_{ijk} is unit variance complex Gaussian random variable (for $i = 1, \cdots N$, $j = 1, \cdots, L$, and $k = 1, \cdots M$). $p_f(j)$ is a constant used for the power shaping of the channel coefficients. Further,

$$10log\frac{p_f(1)}{p_f(j)} = [0 - 5.7 - 7.6 - 10.1 - 13.4 - 16.9 - 17.1] \tag{13}$$

for $j = 1, \cdots, L$. The above values are selected to approximate the UMTS typical urban channel model [8], where the relative delays between the successive fingers correspond to one chip duration. Furthermore, $p_f(1)^2 + \cdots + p_f(L)^2 = 1$ assuring that $E[|h_{i1k}|^2 + \cdots + |h_{iLk}|^2] = 1$ for all i and k.

In Figure 3 we present average capacity of the system in (5), for different number of transmit and receive antennas (MxN). We present the results for flat fading

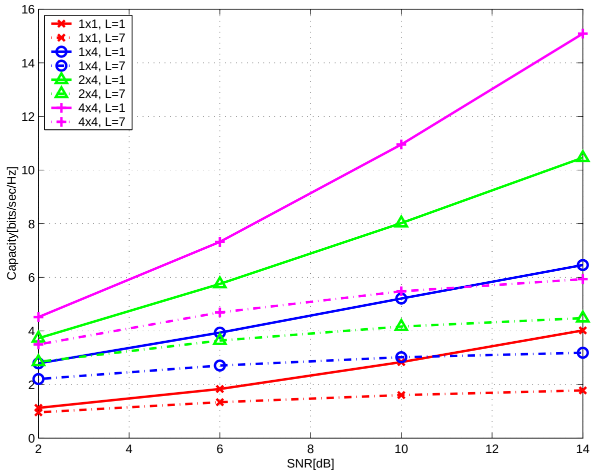

Figure 3: Capacity vs. SNR, $K = 20$, $G = 32$.

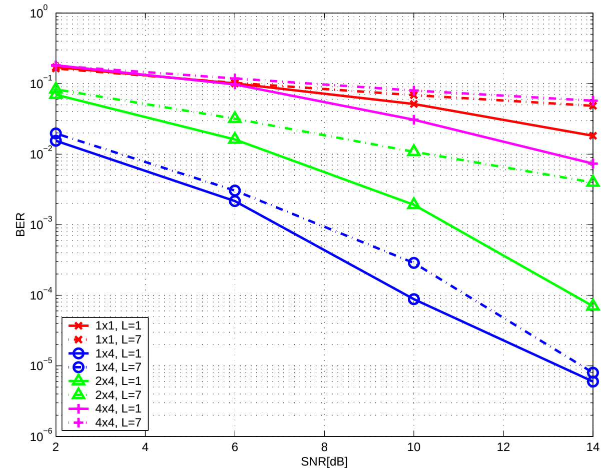

Figure 5: BER vs. SNR, $K = 20$, $G = 32$.

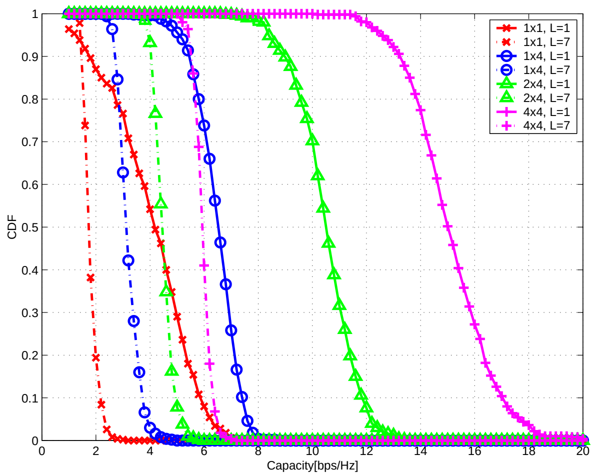

Figure 4: Capacity CDF at SNR $= 14dB$, $K = 20$, $G = 32$.

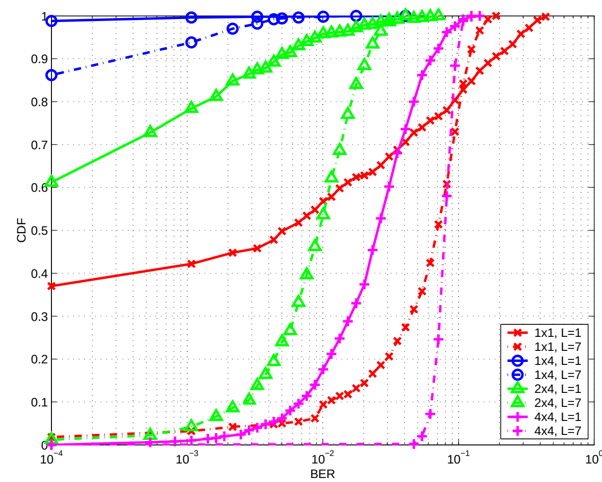

Figure 6: BER CDF at SNR $= 10dB$, $K = 20$, $G = 32$.

channels ($L = 1$) and frequency selective channels assuming that the number of dominant multipath components is $L = 7$ (consequently this is the number of the fingers per antenna). The total number of the users in the cell is set to $K = 20$. These results show significant drop in system capacity for time-dispersive (frequency selective) MIMO channels (for $L = 7$). This is explained as a result of applying the correlator bank as an interface between the wideband MIMO channel and MIMO receiver (in this case it is the VBLAST). This approach assumes that intra-cell MAI introduced by the frequency selective channel is treated as AWGN instead of being processed in more elaborate way (e.g., using chip-level equalization or multi-user detection). Corresponding cumulative statistics (cumulative distribution function - CDF), for SNR $= 14dB$, is given in Figure 4.

In Figure 5 and 6 we present the average BER and its CDF respectively (all for the VBLAST receiver). Also, the total number of the users in the cell is set to $K = 20$. From the results, we infer that in the case of 1x4 systems the performance is almost identical both for the flat-fading and frequency selective fading channels. This confirms well known result which has shown that multiple antenna receiver successfully combats the intra-cell interference [9]. The results for 2x4 are very promising, pointing out that lower BER can be achieved by increasing the ratio between the number of receive vs. transmit antennas.

Further, in Figures 7 and 8 we present the system capacity and VBLAST performance depending on different cell loading (i.e., number of the users in the cell is set to $K = 5$, 10 ,20) and different SNRs. As expected, the capacity and performance of the VBLAST are improved as the cell loading is lowered (resulting in lower

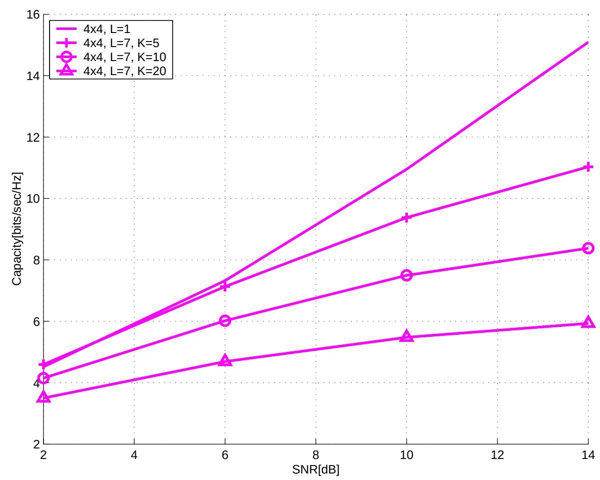

Figure 7: Capacity vs. SNR, in the case of different cell loading, $K = 5$, 10, 20, $G = 32$.

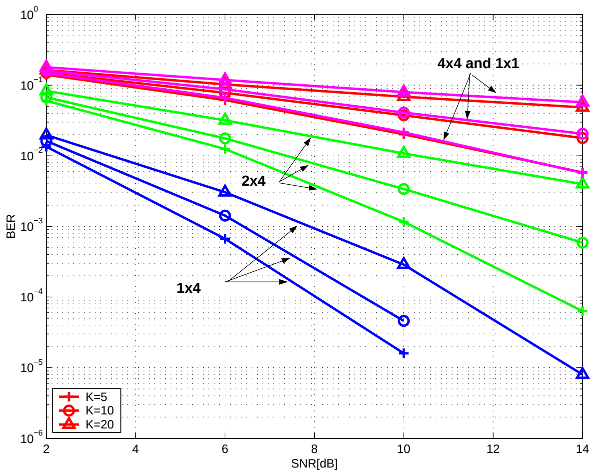

Figure 8: BER vs. SNR, in the case of different cell loading, $K = 5$, 10, 20, $G = 32$.

intra-cell interference). In addition, from Figure 8 note that performance of the 4x4 and 1x1 system, in terms of BER, is practically the same (curves are overlapping), but throughput is four times higher for the 4x4 system, speaking in its favor.

V CONCLUSION

In this paper we have analyzed performance of the VBLAST receiver algorithm. We have assumed that the VBLAST is executed at the symbol rate, following the conventional bank of correlators. We have proposed a model that corresponds to the above system. Concept of virtual antennas has been introduced. Also, we have evaluated the system capacity. Performance of the algorithm in the presence of intra- and inter-cell MAI has been evaluated. The observed system has been defined based on the UMTS physical layer and corresponding channel models. The simulation results have shown significant drop in system capacity for dispersive (frequency selective) MIMO channels. This has been explained as a result of applying the correlator bank as an interface towards the dispersive SISO and/or MIMO channel. This approach treats the intra-cell MAI introduced by the frequency selective channel as AWGN. In wideband case, in order to fully benefit from capacity of the MIMO channel, more sophisticated processing must be applied instead of the conventional correlator bank (e.g., using chip-level equalization or multi-user detection).Application of the correlator bank, as an interface between the channel and MIMO receiver (e.g, VBLAST), is justified in the case of flat fading channels and/or frequency selective channels with low cell loading. Also we have noted that the performance is improved if the ratio between the number of receive vs. transmit antennas is increased.

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