

Maximum-Likelihood Sequence Detection of Multiple Antenna Systems over Dispersive Channels via Sphere Decoding

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Multiple antenna systems are capable of providing high data rate transmissions over wireless channels. When the channels are dispersive, the signal at each receive antenna is a combination of both the current and past symbols sent from all transmit antennas corrupted by noise. The optimal receiver is a maximum-likelihood sequence detector and is often considered to be practically infeasible due to high computational complexity (exponential in number of antennas and channel memory). Therefore, in practice, one often settles for a less complex suboptimal receiver structure, typically with an equalizer meant to suppress both the intersymbol and interuser interference, followed by the decoder. We propose a sphere decoding for the sequence detection in multiple antenna communication systems over dispersive channels. The sphere decoding provides the maximum-likelihood estimate with computational complexity comparable to the standard space-time decision-feedback equalizing (DFE) algorithms. The performance and complexity of the sphere decoding are compared with the DFE algorithm by means of simulations.

Keywords and phrases: sphere decoding, maximum-likelihood, multiple antennas, dispersive channels, computational complexity.

1. INTRODUCTION

Multiple antenna wireless communication systems are capable of providing data transmission at potentially very high rates [1]. To secure high reliability of the data transmission, special attention has to be paid to the design of the receiver. When transmitting over noisy dispersive channels, the received signal at each receive antenna is the combination of the transmitted signals perturbed by noise, intersymbol interference (ISI), and by interuser interference (IUI). In this case, the optimal receiver structure is the multichannel maximum-likelihood sequence estimation (MLSE). However, the computational complexity of the traditional maximum-likelihood sequence detector often prohibits its practical implementation. (For instance, the Viterbi decoder is exponential in the length of the channel [2].) One way to alleviate the computational burden is to settle for (suboptimal) reduced complexity MLSE algorithms by reducing the number of states (see, e.g., [3, 4]). In practice, however, most often a multichannel (space-time) equalizer is used to suppress ISI and IUI first; then, a hard decision is made to recover the symbol that has been sent [2, 5, 6]. The equalizer

may be linear (zero-forcing or minimum mean square), or nonlinear decision-feedback equalizer (DFE). DFEs essentially perform successive interference cancellation: a soft symbol estimate is used to cancel the trailing interference, upon which the hard decision is made to recover the symbol. (For the analysis of the performance of DFE algorithm in a dispersive MIMO environment, see [6].) For high enough SNR, DFEs obtain better performance than linear equalizers while still having much lower complexity than the optimal MLSE algorithm. However, the performance of the DFE is highly inferior compared to the performance of the optimal MLSE algorithm.

In this paper, we propose an algorithm that yields the optimal MLSE performance on dispersive multiple-input multiple-output (MIMO) channels with finite impulse response (FIR). (We should point out that the wireless communication systems may or may not employ feedback from the receiver to the transmitter. In this paper, we focus on optimal detector structures for systems where feedback is unavailable and the receiver learns the channel based on the training information.)

We consider the so-called sphere decoding, an algorithm for solving integer least-squares problems, which, in the communication context, provides the ML estimate of the transmitted data sequence. The algorithm is due to Fincke and Pohst [7] and was first proposed in the context of the closest point searches in lattices (for a review of these, see [8] and the references therein). The algorithm was rediscovered in [9] in the context of detection in GPS systems. The use of the sphere decoding for lattice codes was first proposed in [10], and further investigated in [11, 12]. In [13], it has been analytically shown that the average complexity of the sphere decoding used for ML detection in flat fading multiple-antenna systems is polynomial (often sub-cubic) for a wide range of signal-to-noise ratios (SNRs).

The paper is organized as follows: in Section 2, we describe the FIR MIMO channel model. In Section 3, we pose the detection problem, briefly overview heuristics for solving it, and describe the sphere decoding algorithm. Simulation results are presented in Section 4, where it is shown that the sphere decoding provides significant improvement (several dBs) over the MIMO DFE. The computational complexity of the sphere decoding turns out to be comparable to that of the MIMO DFE, thereby suggesting that it can be implemented in practice. The paper concludes with Section 5.

2. FIR MIMO MODEL DESCRIPTION

We consider a multiple-antenna system with M transmit and N receive antennas. The MIMO channel is modeled as block-fading frequency-selective, where the channel impulse response is constant for some discrete interval T , after which it changes to another (independent) impulse response that remains constant for another interval T , and so on. The additive noise is spatially and temporally independent identically distributed (i.i.d.) circularly-symmetric complex-Gaussian. The MIMO channel model is shown in Figure 1.

The channel is represented by its complex baseband equivalent model. Let the column vector

$$\mathbf{h}^{(i,j)} = [h_1^{(i,j)} \ h_2^{(i,j)} \ \dots \ h_{C^{(i,j)}}^{(i,j)}]'$$
 (1)

denote the single-input single-output (SISO) channel impulse response from the j th transmit to the i th receive antenna. For convenience, we shall make the following assumptions on the SISO channels $\mathbf{h}^{(i,j)}$:

- (1) $C^{(i,j)} = C$, $1 \leq i \leq N$, $1 \leq j \leq M$, that is, all SISO channels have impulse responses of the same length,
- (2) the channel coefficients $h_l^{(i,j)}$, $1 \leq l \leq C$, $1 \leq i \leq N$, $1 \leq j \leq M$ are i.i.d. $\mathcal{C}(0, 1)$.

The received signal at the i th antenna can then be expressed as

$$\chi_k^{(i)} = \sum_{j=1}^M \sum_{l=1}^C h_l^{(i,j)} s_{k-l}^{(j)} + v_k^{(i)},$$
 (2)

for $k = 1, 2, \dots, T + C - 1$. Equation (2) can be written in a

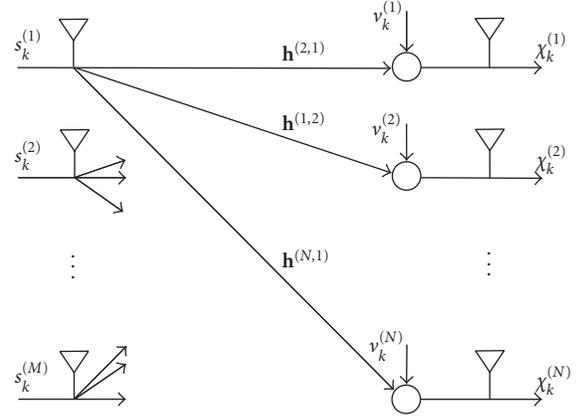


FIGURE 1: FIR MIMO channel model.

matrix form as

$$\mathcal{X}_k = \sum_{l=1}^C H_l \mathcal{S}_{k-l} + \mathcal{V}_k, \quad (3)$$

where

$$\mathcal{S}_k = [s_k^{(1)} \ s_k^{(2)} \ \dots \ s_k^{(M)}]'$$
 (4)

is the transmit vector, whose entries typically come from a QAM constellation, $\mathcal{V}_k \in \mathcal{C}^{N \times 1}$ is the additive noise vector defined as

$$\mathcal{V}_k = [v_k^{(1)} \ v_k^{(2)} \ \dots \ v_k^{(N)}]'$$
 (5)

and $H_l \in \mathcal{C}^{N \times M}$ is the l th coefficient matrix in the MIMO channel impulse response,

$$H_l = \begin{bmatrix} h_l^{(1,1)} & h_l^{(1,2)} & \dots & h_l^{(1,M)} \\ h_l^{(2,1)} & h_l^{(2,2)} & \dots & h_l^{(2,M)} \\ \vdots & \vdots & \ddots & \vdots \\ h_l^{(N,1)} & h_l^{(N,2)} & \dots & h_l^{(N,M)} \end{bmatrix}. \quad (6)$$

In other words, the z -transform of the MIMO channel impulse response is given by

$$H(z) = H_1 + H_2 z^{-1} + \dots + H_C z^{-(C-1)}. \quad (7)$$

Define the following vectors:

$$\begin{aligned} \mathcal{X} &= [\mathcal{X}'_1 \ \mathcal{X}'_2 \ \dots \ \mathcal{X}'_{T+C-1}]', \\ \mathcal{V} &= [\mathcal{V}'_1 \ \mathcal{V}'_2 \ \dots \ \mathcal{V}'_{T+C-1}]', \\ \mathcal{S} &= [\mathcal{S}'_1 \ \mathcal{S}'_2 \ \dots \ \mathcal{S}'_T]'. \end{aligned} \quad (8)$$

(Note that the random vector $\mathcal{V} \in \mathcal{C}^{N(T+C-1)}$ has unit variance complex Gaussian i.i.d. entries, $E[\mathcal{V} \mathcal{V}^*] = I_{N(T+C-1)}$.) Then from (3) we can write the input-output relation for the

to obtain a reduced integer least-squares problem with $2MT - 1$ unknowns. Then the procedure is repeated to solve similarly for $s^{(2)}$, and so on. (Nulling and cancelling is fundamentally equivalent to the generalized decision-feedback equalization discussed in [15].) As a side note, one can further improve the performance of nulling and canceling by introducing optimal ordering: the algorithm starts from the “strongest” and proceeds to the “weakest” entry in \mathbf{s} (see, e.g., [14, 16]).

The aforementioned heuristics have acceptable polynomial-time computational complexity for practical implementation purposes. However, their performance is inferior in comparison with the exact solution to the MLSE problem.

We proceed by describing an algorithm, the so-called *sphere decoding*, for efficient closest point search in the lattice.

3.1. Sphere decoding

The sphere decoding performs the closest-point search in a somewhat more sophisticated manner than doing a full search over the integer lattice, which requires exponential complexity. In particular, it performs search only over lattice points lying in a certain hypersphere of radius r centered around the received vector \mathbf{x} . The closest lattice point is clearly the solution.

From a practical point of view, there are two issues that have to be resolved. One is the proper choice of the sphere radius r : if r is too large there will be too many lattice points in the sphere and we may still require an exponential search; if r is too small there will be no points in the sphere. The other issue concerns determining which lattice points lie within the sphere—if the algorithm were to check all the points in the lattice, we would be again stuck with an exponential search.

We use a statistical criterion to choose radius r . In particular, the radius of the sphere is chosen so that with high probability we find at least one lattice point in the sphere. To this end, note that

$$\|\mathbf{v}\|^2 = \|\mathbf{x} - \mathbf{H}\mathbf{s}\|^2 \quad (18)$$

is a chi-square random variable with NT degrees of freedom. (Recall that each entry on \mathbf{v} is an independent $N(0, \sigma^2)$ random variable.) We choose the radius r to be a linear function of the variance of $\|\mathbf{v}\|^2$,

$$r^2 = \alpha 2NT\sigma^2, \quad (19)$$

where the coefficient α is chosen in such a way that with a high probability p_{fp} we find a lattice point inside a sphere,

$$\int_0^{\alpha 2NT} \frac{\lambda^{NT-1}}{\Gamma(NT)} e^{-\lambda} d\lambda = p_{\text{fp}}. \quad (20)$$

We find α in (20) by a simple table lookup.

Once we have chosen radius r , we need to determine which lattice points belong to the sphere of radius r . An efficient way to check whether a lattice point belongs to the sphere is given by the algorithm of Fincke and Pohst [7]. Note

that \mathbf{s} lies in a sphere of radius r if

$$r^2 \geq \|\mathbf{x} - \mathbf{H}\mathbf{s}\|^2 = (\mathbf{s} - \hat{\mathbf{s}})^* \mathbf{H}^* \mathbf{H} (\mathbf{s} - \hat{\mathbf{s}}) + \|\mathbf{x}\|^2 - \|\mathbf{H}\hat{\mathbf{s}}\|^2, \quad (21)$$

where $\hat{\mathbf{s}} = \mathbf{H}^\dagger \mathbf{x}$. To make the notation simpler, denote size of the vector \mathbf{s} as

$$m = 2MT. \quad (22)$$

(Note that m is the number of unknowns and it will be of interest in studying the complexity.)

Introducing the QR decomposition $\mathbf{H} = \mathbf{Q}\mathbf{R}$ (where \mathbf{Q} is unitary and \mathbf{R} is upper triangular), and defining $r'^2 = r^2 - \|\mathbf{x}\|^2 + \|\mathbf{H}\hat{\mathbf{s}}\|^2$, we can write (21) as

$$\begin{aligned} r'^2 &\geq (\mathbf{s} - \hat{\mathbf{s}})^* \underbrace{\mathbf{R}^* \mathbf{Q}^* \mathbf{Q}}_{=\mathbf{I}} \mathbf{R} (\mathbf{s} - \hat{\mathbf{s}}) \\ &\geq (\mathbf{s} - \hat{\mathbf{s}})^* \mathbf{R}^* \mathbf{R} (\mathbf{s} - \hat{\mathbf{s}}) \\ &= \sum_{i=1}^m r_{ii}^2 \left(s_i - \hat{s}_i + \sum_{j=i+1}^m \frac{r_{ij}}{r_{ii}} (s_j - \hat{s}_j) \right)^2 \\ &= r_{mm}^2 (s_m - \hat{s}_m)^2 \\ &\quad + r_{m-1,m-1}^2 \left(s_{m-1} - \hat{s}_{m-1} + \frac{r_{m-1,m}}{r_{m-1,m-1}} (s_m - \hat{s}_m) \right)^2 + \dots, \end{aligned} \quad (23)$$

where $r_{i,j}$ denotes (i, j) entry of the matrix \mathbf{R} . A necessary condition for \mathbf{s} to lie inside the sphere is therefore that

$$r_{mm}^2 (s_m - \hat{s}_m)^2 \leq r'^2. \quad (24)$$

This condition is easy to check and it leads to

$$\left[\hat{s}_m - \frac{r'}{r_{mm}} \right] \leq s_m \leq \left[\hat{s}_m + \frac{r'}{r_{mm}} \right]. \quad (25)$$

However, condition (25) is by no means sufficient. For every s_m satisfying (25), upon defining $r_{m-1}^2 = r'^2 - r_{mm}^2 (s_m - \hat{s}_m)^2$ one can state a stronger necessary condition

$$r_{m-1,m-1}^2 \left(s_{m-1} - \hat{s}_{m-1} + \underbrace{\frac{r_{m-1,m}}{r_{m-1,m-1}} (s_m - \hat{s}_m)}_{\hat{s}_{m-1|m}} \right)^2 \leq r_{m-1}^2, \quad (26)$$

which is equivalent to

$$\left[\hat{s}_{m-1|m} - \frac{r'_{m-1}}{r_{m-1,m-1}} \right] \leq s_{m-1} \leq \left[\hat{s}_{m-1|m} + \frac{r'_{m-1}}{r_{m-1,m-1}} \right]. \quad (27)$$

In a similar fashion, one proceeds for s_{m-2} , and so on, stating nested necessary conditions for all elements of \mathbf{s} . This leads us to the sphere decoding algorithm which essentially finds all points that satisfy the previously stated conditions:

Input: $R, \mathbf{x}, \hat{\mathbf{s}}, r$.

- (1) Set $k = m$, $r'_m = r^2 - \|\mathbf{x}\|^2 + \|\mathbf{H}\hat{\mathbf{s}}\|^2$, $\hat{s}_{m|m+1} = \hat{s}_m$.
- (2) (Bounds for s_k) set $z = r'_k / r_{kk}$, $UB(s_k) = \lfloor z + \hat{s}_{k|k+1} \rfloor$, $s_k = \lceil -z + \hat{s}_{k|k+1} \rceil - 1$.

- (3) (Increase s_k) $s_k = s_k + 1$. If $s_k \leq UB(s_k)$ go to (5), else to (4).
- (4) (Increase k) $k = k + 1$; if $k = m + 1$, terminate algorithm, else go to (3).
- (5) (Decrease k) if $k = 1$ go to (6). Else $k = k - 1$, $\hat{s}_{k|k-1} = \hat{s}_k + \sum_{j=k+1}^m (r_{kj}/r_{kk})(s_j - \hat{s}_j)$, $r_k'^2 = r_{k+1}^2 - r_{k+1,k+1}^2 (s_{k+1} - \hat{s}_{k+1|k+2})^2$, and go to (2).
- (6) Solution found. Save \mathbf{s} and go to (3).

In general, the closest point search has both worst-case and average complexity that is exponential in the number of unknowns [17]. The same is true for the sphere decoding. However, in our application, the vector \mathbf{x} in (16) is not an arbitrary point in space but rather a lattice point perturbed by the noise as expressed by (14). Clearly, the higher the SNR in (12), the less perturbed the lattice point is. Therefore, one may suspect that the expected complexity of the sphere decoding algorithm will depend on the SNR. Indeed, this is the case—the higher the SNR, the lower the complexity.

In [13], we have computed in closed-form the expected complexity (averaged over the noise and the lattice) of the sphere decoding for the nondispersive (flat-fading) channels. It is shown that the expected complexity is polynomial-time over a wide range of SNRs, and is, in fact, often sub-cubic for SNRs that support the data rates being transmitted.

For dispersive channels explicitly computing the expected complexity appears to be much more complicated, and we are currently not able to analytically perform all the required steps. Nonetheless, simulation suggest the same qualitative performance of polynomial-time complexity as we observe from the examples in Section 4.

Furthermore, the complexity of the sphere decoding can be improved by exploiting the Toeplitz structure of the channel matrix. In particular, note that the channel matrix preprocessing is required only in order to transform \mathbf{H} into an upper triangular form. Due to the Toeplitz structure of \mathbf{H} , it is in fact sufficient to perform QR factorization of only one coefficient matrix in the MIMO channel impulse response (H_C in (10)). Upon QR factorization of H_C the bottom square submatrix of \mathbf{H} becomes upper triangular and thus can be processed by the sphere decoding algorithm to find a lattice point \mathbf{s} ; then one proceeds by adding the contribution of the top $2(C - 1)$ rows of \mathbf{H} to find the metric $\|\mathbf{x} - \mathbf{H}\mathbf{s}\|^2$ and by testing whether the lattice point \mathbf{s} belongs to the sphere.

Further improvement in the complexity of the sphere decoding can be obtained by employing the Schnorr-Euchner variation of the Fincke-Pohst algorithm (see [8, 18]). Essentially, by examining points in the hypersphere in a different order (in particular, by starting from the Babai point), significant computational savings can be obtained [18].

4. SIMULATION RESULTS

We first consider a communication system with $M = 2$ transmit and $N = 2$ receive antennas. The channel memory is assumed to be $C = 4$, and the coherence interval time $T = 4$. Data is modulated onto 4-QAM constellation

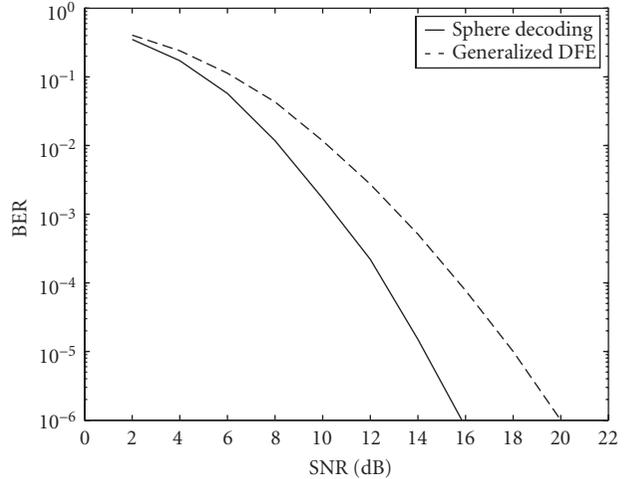


FIGURE 3: BER performance of SD and DFE for $M = 2$, $N = 2$, $C = 4$, $T = 4$, $L = 2$.

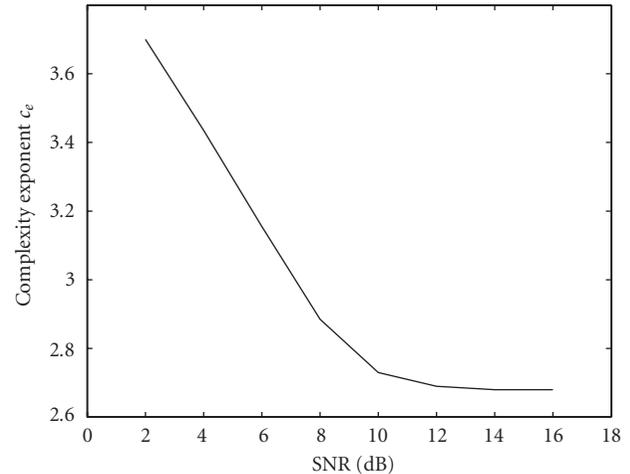


FIGURE 4: Complexity exponent of the SD for $M = 2$, $N = 2$, $C = 4$, $T = 4$, $L = 2$.

(corresponding to 2-PAM, or $L = 2$, in the real-valued set of (14)). The resulting transmission rate is therefore 4 bits/channel use. The performance comparison of an uncoded transmission in terms of bit error rate (BER) between the sphere decoding and nulling and canceling (or, equivalently, generalized DFE) is shown in Figure 3.

As an indicator of the expected computational complexity of the sphere decoding, we adopt the complexity exponent, c_e , defined as

$$c_e = \frac{\log(\text{expected total flop count})}{\log(m)}, \quad (28)$$

where m is defined in (22). The expected complexity can therefore be expressed as

$$O(m^{c_e}) = O((2MT)^{c_e}). \quad (29)$$

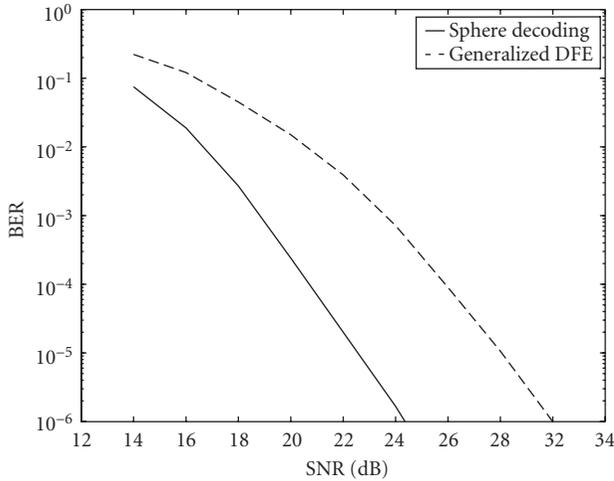


FIGURE 5: BER performance of SD and DFE for $M = 2$, $N = 2$, $C = 4$, $T = 8$, $L = 4$.

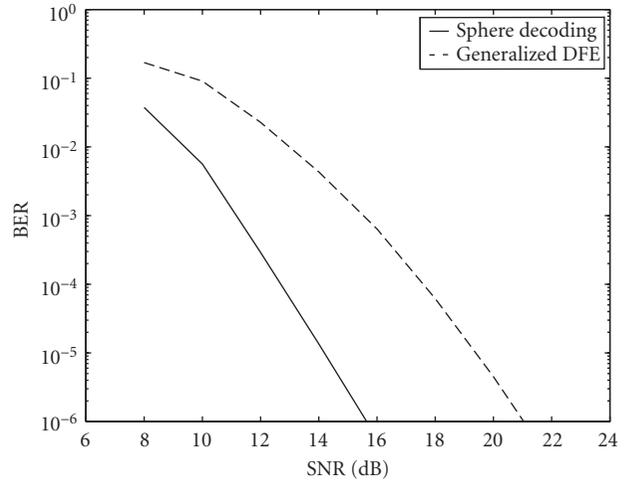


FIGURE 7: BER performance of SD and GDFE for $M = 4$, $N = 4$, $C = 4$, $T = 8$, $L = 4$.

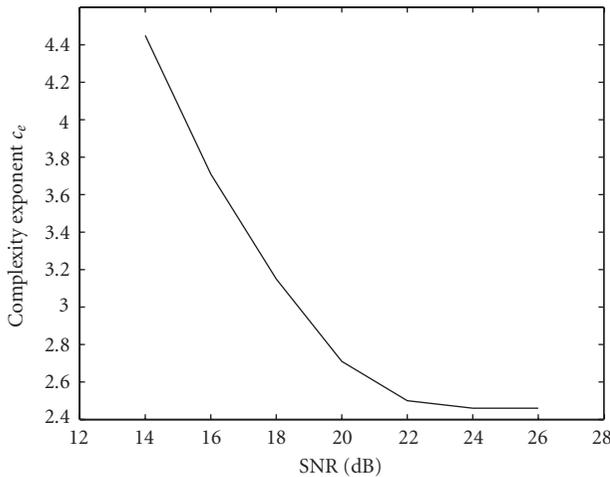


FIGURE 6: Complexity exponent of the SD for $M = 2$, $N = 2$, $C = 4$, $T = 8$, $L = 4$.

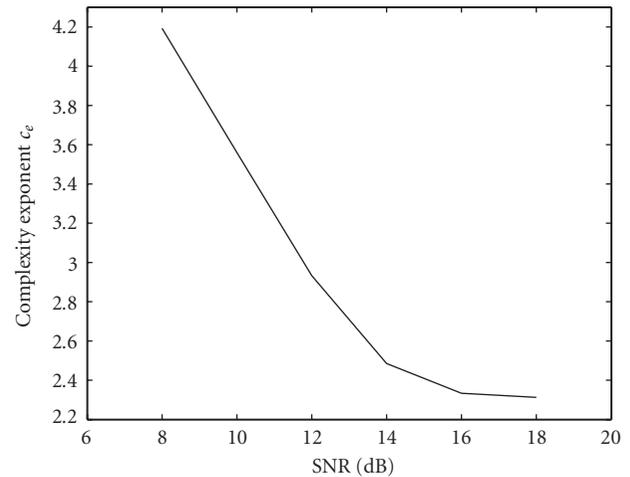


FIGURE 8: Complexity exponent of the SD for $M = 4$, $N = 4$, $C = 4$, $T = 8$, $L = 4$.

The complexity exponent as the function of SNR for the previous example with $m = 16$ is shown in Figure 4. Note that for SNRs above 7 dB we obtain sub-cubic complexity.

As another example, we consider the same 2×2 system ($M = 2$, $N = 2$), with $C = 4$, but now increase the block length to $T = 8$, and the constellation to 16-QAM, corresponding to $L = 4$ and a transmission rate of 8 bits/channel use. The performance comparison between the sphere decoding and generalized DFE is shown in Figure 5. The complexity exponent as the function of SNR for this example (where $m = 32$) is shown in Figure 6.

As a final example, consider the 4×4 communication system ($M = 4$, $N = 4$), with $C = 4$ and block length $T = 8$ (and thus $m = 64$). The constellation used is 4-QAM (hence $L = 2$, and the corresponding transmission rate is 8 bits/channel use). The performance comparison between sphere decoding and generalized DFE for this system is shown in Figure 7. The

corresponding complexity exponent of the sphere decoding is shown in Figure 8 and is sub-cubic for SNRs above 12 dB.

5. DISCUSSION AND CONCLUSION

We have proposed sphere decoding for maximum-likelihood sequence detection of multiple antenna systems over frequency-selective channels. To employ the sphere decoding, the detection problem was posed as an integer least-squares problem. As illustrated by simulations, the sphere decoding provides several dBs improvement over the MIMO decision-feedback equalization. We have shown empirically that the expected computational complexity of the sphere decoding is polynomial (often sub-cubic) for a wide range of SNRs. Both the sphere decoding and MIMO DFE require some preprocessing of the channel matrix (usually in a form of QR factorization) which, in general, has cubic

complexity. Therefore, the maximum-likelihood detection on MIMO channels with memory can be implemented with complexity similar to that of heuristic methods, but with significant performance gains.

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- Distributed coding/decoding
- Efficient decoder design

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| Manuscript Due | November 1, 2007 |
| First Round of Reviews | February 1, 2008 |
| Publication Date | May 1, 2008 |

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**6th International Symposium on
COMMUNICATION SYSTEMS, NETWORKS AND DIGITAL SIGNAL PROCESSING (CSNDSP'08)
23-25 July 2008, Graz University of Technology, Graz, Austria
www.csndsp.com**

Hosted by: Institute of Broadband Communications, Department of Communications and Wave Propagation

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First Call for Papers

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Following the success of the last event, and after 10 years, the CSNDSP steering committee decided to hold the next event at the Graz University, Austria. Graz was the 2003 cultural capital of Europe. CSNDSP, a biannual conference, started in UK ten years ago and in 2006 it was held for the first time outside UK in Patras/Greece. CSNDSP has now been recognised as a forum for the exchange of ideas among engineers, scientists and young researchers from all over the world on advances in communication systems, communications networks, digital signal processing and other related areas and to provide a focus for future research and developments. The organising committee invites you to submit original high quality papers addressing research topics of interest for presentation at the conference and inclusion in the symposium proceedings.

Papers are solicited from, but not limited to the following topics:

- Adaptive signal processing
 - ATM systems and networks
 - Chip design for Communications
 - Communication theory
 - Coding and error control
 - Communication protocols
 - Communications for disaster management
 - Crosslayer design
 - DSP algorithms and applications
 - E-commerce and e-learning applications
 - Intelligent systems/networks
 - Internet communications
 - High performance networks
 - Mobile communications, networks, mobile computing for e-commerce
 - Mobility management
 - Modulation and synchronisation
 - Modelling and simulation techniques
 - Multimedia communications and broadband services
 - Microwave Communications
 - New techniques in RF-design and modelling
 - Network management & operation
 - Optical communications
 - Optical MEMS for lightwave networks
 - RF/Optical wireless communications
 - Photonic Network
 - Quality of service, reliability and performance modelling
 - Radio, satellite and space communications
 - RFID & near field communications
 - Satellite & space communications
 - Speech technology
 - Signal processing for storage
 - Teletraffic models and traffic engineering
 - VLSI for communications and DSP
 - Wireless LANs and ad hoc networks
 - 3G/4G network evolution
 - *Any other related topics*
- Papers may be presented in the form of **Oral presentation and/or Poster**
- Contributions by **MPhil/PhD research students** are particularly encouraged.

Submission Dates:

- **Full Paper due:** 27th Jan. 2008
- **Notification of acceptance by:** 1st April 2008
- **Camera ready paper due:** 5th May 2008

- Electronic submission by e-mail to: csndsp08@tugraz.at
- All papers will be refereed and published in the symposium proceeding. Selected papers will be published in: *The Mediterranean Journals of Computers and Networks* and *Electronics and Communications*, and possibly *IET proceedings*.
- **A number of travel grants and registration fee waivers will be offered to the delegates.**

Fees: 360.00 EURO, (Group Delegates of 3 persons: 760.00 Euro)

Includes: A copy of the Symposium Proceedings, Lunches, and Symposium Dinner on the 24th July.

CSNDSP'08 General Information

Contact: **Dr. Erich Leitgeb** - *Local Organising Committee Chair*

- Institute of Broadband Communications, Graz University of Technology, A-8010 Graz, Inffeldg. 12, Tel.: ++43-316-873-7442, Fax.: ++43-316-463697.
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CALL FOR PAPERS

3DTV CONFERENCE 2008

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Following the conference of 2007, the second 3DTV Conference will be held in Istanbul, Turkey in May, 2008. The aim of 3DTV-Con is to bring researchers from different locations together and provide an opportunity for them to share research results, discuss the current problems and exchange ideas.

The conference involves a wide range of research fields such as capturing 3D scenery, 3D image processing, data transmission and 3D displays. You are cordially invited to attend 3DTV-Con 2008 and submit papers reporting your work related to the conference themes listed below.

Conference Topics

3D Capture and Processing:

- 3D time-varying scene capture technology
- Multi-camera recording
- 3D photography algorithms
- Dense stereo and 3D reconstruction
- Synchronization and calibration of camera arrays
- 3D view registration
- Multi-view geometry and calibration
- Holographic camera techniques
- 3D motion analysis and tracking
- Surface modeling for 3D scenes
- Multi-view image and 3D data processing
- Integral imaging techniques

3D Transmission:

- Systems, architecture and transmission in 3D
- 3D streaming
- Error-related issues and handling of 3D video
- Hologram compression
- Multi-view video coding
- 3D mesh compression
- Multiple description coding for 3D
- Signal processing for diffraction and holographic 3DTV

3D Visualization:

- 3D mesh representation
- Texture and point representation
- Object-based representation and segmentation
- Volume representation
- 3D motion animation
- Stereoscopic display techniques
- Holographic display technology
- Reduced parallax systems
- Underlying optics and VLSI technology
- Projection and display technology for 3D videos
- Integral imaging techniques
- Human factors

3D Applications:

- 3D imaging in virtual heritage and virtual archaeology
- 3D teleimmersion and remote collaboration
- Augmented reality and virtual environments
- 3D television, cinema, games and entertainment
- Underlying Technologies for 3DTV
- Medical and biomedical applications
- 3D content-based retrieval and recognition
- 3D watermarking

Paper Submission

Contributors are invited to submit full papers electronically using the online submission interface, following the instructions at <http://www.3dtv-con.org>. Papers should be in Adobe PDF format, written in English, with no more than four pages including figures, with a font size of 11. Conference proceedings will be published online by IEEE Xplore.

Important Dates

| | |
|--|------------------|
| Special sessions and tutorials proposals deadline: | 14 December 2007 |
| Regular paper submission deadline: | 11 January 2008 |
| Notification of paper acceptance: | 29 February 2008 |
| Camera-ready paper submission deadline: | 21 March 2008 |
| Conference: | 28-30 May 2008 |

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